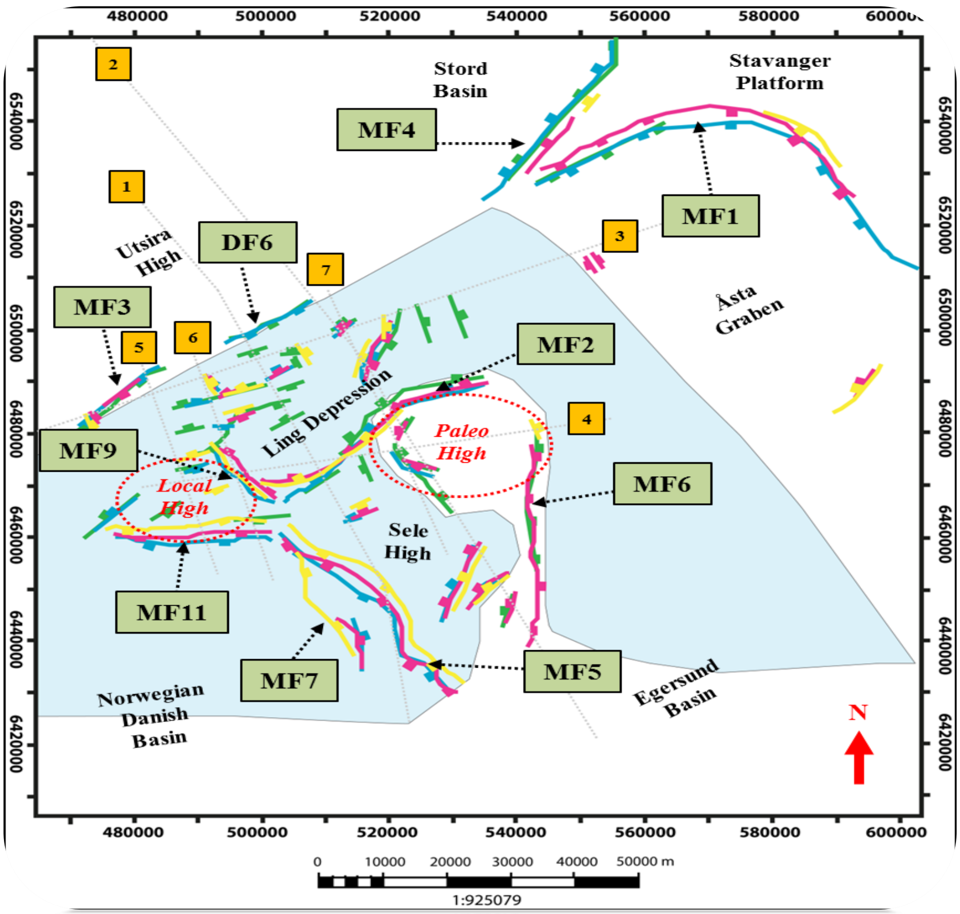
Master Thesis, Department of Geosciences

Structure and evolution of the Ling Depression and adjacent highs in the central North Sea

Taimur Jahangir Khan



UNIVERSITY OF OSLO
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Structure and evolution of the Ling Depression and adjacent highs in the central North Sea

Taimur Jahangir Khan

Master Thesis in Geosciences

Discipline: Petroleum Geology and Geophysics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

University of Oslo

June 2013

ABSTRACT

The Ling Depression is a structural feature with a unique orientation in the Central North Sea which depicts the trend and linkage of deep extensional zones with the overlying structures. The Ling Depression is studied and analyzed to extract information leading to the geological evolution of the study area.

The data of regional seismic lines along with borehole information was assembled and used for the structural and stratigraphic analysis. Mapping of the key horizons was performed and time-structure maps along with time-thickness maps were generated. Further onwards, detailed analyses on different fault geometries and style of faulting were carried out. These exercises facilitated in extracting in-depth details of the key structural elements and finally comprehend the geological evolution of the Ling Depression and the adjacent highs.

Horst geometries are interpreted which are bounded by deep-rooted brittle faults, probably linking with a major Devonian basement shear zone, the Hardangerfjord Shear Zone. Some clear rotated half-grabens are observed below the Base Zechstein within the Ling Depression. Large salt diapirs breaching into the Mesozoic-Cenozoic stratigraphy mostly in the SW of the study area are also noticed. Large-scale monoclinal fold structures are interpreted at the shallower stratigraphic level in the study area. The primary depo-centers are determined using the time-thickness maps between the certain stratigraphic levels.

In the light of the obtained results, it is assumed that the basement shear zones of the Early Devonian age have played an important role in shaping the local geometries and features in the study area. Major half-grabens observed are confined to the Late Carboniferous-Early Permian rifting event along with the reactivation of certain deep-rooted fault geometries. The Zechstein salt has acted as décollement, hence separating Jurassic rifting from the Late Carboniferous-Early Permian rifting, which all together affected and evolved the local structural elements. Alpine compression further introduced inverted structures and faults in the Ling Depression

ACKNOWLEDGEMENT

I feel instigated from within to extend my steadfast thanks to ALMIGHTY ALLAH whose blessings enabled me to perceive and purse my ambitions and objectives. Special praises to my beloved Prophet Muhammad PBUH, who is bellwether for humanity as a whole.

I feel great honor in expressing my avid gratifications to my supervisors Dr. Michael Heeremans and Prof. Jan Inge Faleide, under whose dynamic supervision, auspicious and considerate guidance, encouragement and altruistic attitude, I was able to accomplish work presented in this dissertation.

Special thanks to Aftab Javed Mirza, Muhammad Aftab and Muhammad Assad for their support and for the help during the course of this thesis.

In the end my whole hearted and incessant gratitude to my loving parents (especially my mother), my brothers and my sister, who always appreciated, encouraged and helped me during my eighteen years of studies.

Taimur Jahangir Khan

Contents

ABSTRACT i
ACKNOWLEDGEMENT iii
Contents iv
CHAPTER 1 1
INTRODUCTION 1
1.1. General 1
1.2. Objective 2
CHAPTER 2 3
REGIONAL STRUCTURAL AND STRATIGRAPHIC FRAMEWORK 3
2.1. Regional geological and structural settings 3
2.1.1. Structures related to the Caledonian Orogeny 3
2.1.2. Devonian tectonics history 5
2.1.2.1. Devonian history of the Basement shear zones 7
2.1.3. The Variscan Orogeny and the Carboniferous tectonic history 8
2.1.4. Permian tectonics 8
2.1.5. Tectonic events in the Mesozoic period 9
2.2. Regional stratigraphic framework 10
2.2.1. Devonian stratigraphy 10
2.2.1.1. Lower Old Red group 10
2.2.1.2. Middle Old Red group 10
2.2.1.3. Upper Old Red group 11
2.2.2. Carboniferous stratigraphy 11
2.2.3. Permian stratigraphy 11
2.2.4. Triassic stratigraphy 12
2.2.5. Jurassic stratigraphy 12
2.2.6. Cretaceous stratigraphy 12
2.3. Structural elements 13
2.3.1. Hardangerfjord Shear Zone 13
2.3.2. Ling Depression 13

2.3.3. Utsira High 14
2.3.4. Sele High 14
CHAPTER 3 17
DATA AND METHODOLOGY 17
3.1. Introduction 17
3.2. Data 18
3.2.1. Regional 2-D seismic profiles 18
3.2.2. Well data 18
3.3. Interpretation method 21
CHAPTER 4 25
SEISMIC INTERPRETATION AND RESULTS 25
4.1. Introduction 25
4.2. Composite fault map 25
4.2.1. MF1 27
4.2.2. MF2 27
4.2.3. MF3 27
4.2.4. MF4 27
4.2.5. MF5 27
4.2.6. MF6 28
4.2.7. MF7 28
4.2.8. MF9 28
4.2.9. MF11 28
4.2.10. DF6 28
4.3. Description of key seismic profiles 29
4.3.1. Key seismic profile 1 29
4.3.2. Key seismic profile 2 33
4.3.3. Key seismic profile 3 37
4.3.4. Key seismic profile 4 38
4.3.5. Key seismic profile 5 40
4.3.6. Key seismic profile 6 41
4.3.7. Key seismic profile 7 43

4.4. Time-structure (TWT) and fault maps 55
4.4.1. Base Zechstein (mid-Permian) stratigraphic level 56
4.4.2. Base Triassic stratigraphic level 59
4.4.3. Mid-Jurassic stratigraphic level 60
4.4.4. Base Chalk (mid-Cretaceous) stratigraphic level 61
4.5. Time-thickness maps 62
4.5.1. Late Permian (Zechstein salt) time-thickness map 62
4.5.2. Time-thickness map from mid-Jurassic to Base Chalk....63
CHAPTER 5 69
DISCUSSION 69
5.1. Devonian Extensional event 69
5.2. Late Carboniferous-Early Permian rifting event....70
5.2.1. Linked half-grabens within the Ling Depression....70
5.2.2. Syn-rift and post-rift transition during the Late Permian....71
5.3. Triggering of the Zechstein salt in the Triassic 71
5.4. Late Jurassic rifting event 73
5.5. Inversion during the Late Cretaceous 73
5.5.1. Alpine compression and salt movement 73
5.6. Architecture and role of deep faults in the study area 75
5.6.1. Local inversion in the Late Devonian-Early Carboniferous 76
5.6.2. Reactivation of deep faults during later rift events 76
5.7. Half-graben geometries present below the Base Zechstein 81
5.8. Distribution of the Zechstein salt in the study area....82
5.9. Lateral fault configuration 85
CHAPTER 6 87
SUMMARY AND CONCLUSION 87
REFERENCES 89

CHAPTER 1

INTRODUCTION

1.1. General

The North Sea area has evolved through time with several tectonic events introducing complex geological features. As far as the geology of the North Sea is concerned, the post-Caledonian period is of great importance. Some major extensional shear zones were formed in the Early Devonian time during the collapse of the Caledonian Orogeny (Fossen, 1992). These large scale detachment zones are related to extension rather than mountain building (Andersen et al., 1999) and lately reactivated during E-W to NW-SE extensional settings, hence introducing complex geometries in the North Sea area.

The general location of the study area is shown on the regional map (fig. 1.1). The Ling depression in the Central North Sea is the NE-SW oriented structure and is possibly formed as result of the reactivation of the Hardangerfjord Shear Zone running beneath it. These large shear zones, produced during the Post-Caledonian extension, are of great interest in the onshore-offshore correlation (Séranne and Seguret, 1987; Andersen and Jamtveit, 1990; Fossen and Rykkelid, 1992a; Milnes et al., 1997; Olesen et al., 2002; Skilbrei et al., 2002). One of the key structures that affected both the Southern Norway mainland and the framework of the North Sea is the Hardangerfjord Shear Zone (Fossen and Hurich, 2005). The Ling Depression also separates the Utsira High towards the north and the Sele High towards the South. The Ling Depression has a great significance in terms of tectonic features, as it helps in order to study the changes in structural style of the Central North Sea. Together with the Åsta Graben, it also marks the northern boundary for the Zechstein salt (Heeremans and Faleide, 2004).

The study area has recently gained more importance because of the oil findings on the Utsira High. There are only few wells which have penetrated deep in to the pre-Zechstein stratigraphy in the Northern Permian Basin (Heeremans and Faleide, 2004). One recent well (16/8-3S) was drilled in the Ling Depression upto the Rotliegend group of the Early Permian age. It was the exploration well to prove the petroleum potential of the Early Permian Rotliegend group in the Ling Depression but unfortunately the reservoir quality was poor in the Rotliegendes and the well went out dry (npd.no).

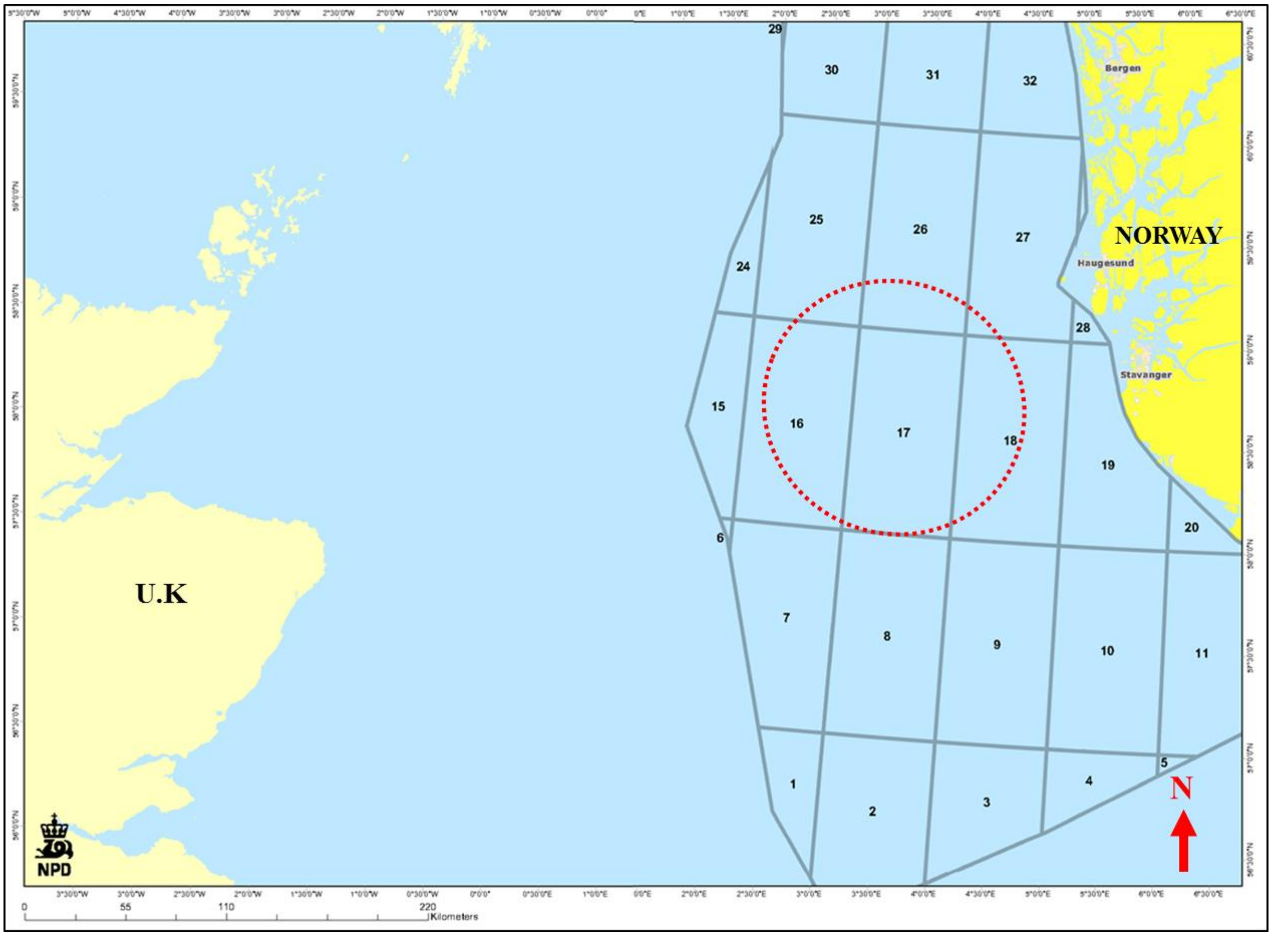


Figure 1.1: Regional map showing the location of the study area encircled in red. The numbers on map are showing the block locations in the Norwegian North Sea. Scale for the map is given in the lower left corner (npd.no/ fact maps)

1.2. Objective

The main objective of this thesis is to study and understand the geological evolution of the Ling Depression and its adjacent highs during different times. The main emphasize is on the timing and style of faulting along with the reconstruction of the basin evolution. Structural analysis, interpretation and study of the pre-Permian faults are conducted, in order to understand the tectonic framework and to predict the fault trends which are associated with the deep structures. Time-structure maps and time-thickness maps are generated at certain stratigraphic levels to further determine the evolution of the study area.

CHAPTER 2

REGIONAL STRUCTURAL AND STARTIGRAPHIC FRAMEWORK

2.1. Regional geological and structural settings

Since Cambrian times, the North Sea has undergone several tectonic events which include both compressional and extensional events. The tectonic events which have shaped the area under consideration are (Ziegler, 1990):

1. Caledonian orogeny which was the result of the collision between Baltica, Avalonia and Laurentia in the Late Ordovician to the Middle Silurian.
2. Collapse of the Caledonian Orogeny in the Early Devonian, resulting in the formation of the Devonian basins and large extensional shear zones.
3. Tectonic rifting in the Late Carboniferous-Early Permian resulted in the formation of several basins and further resulted in the formation of half-graben structures in the North Sea.
4. Late Jurassic rifting which is represented by NNE-SSW structural orientation (Smethurst, 2000)
5. Basin inversion due to reactivation of pre-existing faults and structures from the Late Cretaceous- Early Cenozoic.

2.1.1. Structures related to the Caledonian Orogeny

There were two suture zones developed by the collision of the continents at the time of the Caledonian orogeny. The suture developed towards the east, between Baltica and eastern Avalonia, is called the Thor Suture or the Trans-European Fault (Berthelsen, 1993) and the one developed on the western side between Avalonia and Laurentia is called the Iapetus suture (fig. 2.1; Thybo, 1997). The Caledonian deformation front marks the limit of folding and thrusting of the décollement towards the Baltic craton by which the Early Paleozoic sedimentation and the Precambrian basement were affected (Ziegler, 1990). Models generated from seismic velocity and density provides evidence that the Avalonian crust is less dense than the Baltic crust and their transition is represented by the Caledonian Deformation Front (fig. 2.2; Abramovitz et al., 1998, 1999; Abramovitz and Thybo, 2000; Wiliamson et al., 2002). The 825 Ma old Precambrian basement to the NE is also separated by the Caledonian Deformation Front, from the 450-415 Ma Caledonian basement to the SW (Frost et al., 1981; MONA LISA working group. 1997b). There is a connection between these suture zones, formed by the Caledonian collision, and the rifting events which occurred later in this area (Lyngsie et al., 2006). The Caledonian collision resulted in the formation of deep foreland basins on the Baltic plate in front of the Danish-North German Caledonides (Thybo, 1990, 2001). The build-up of the Caledonian Orogeny continued in the Early Devonian (Woodcock and Strachan, 2000; Bluck, 2001). Due to the oblique collision, sinistral strike-slip movements occurred along several faults such as the Highland Boundary Fault and the Great Glen Fault (Marshall and Hewett, 2003).

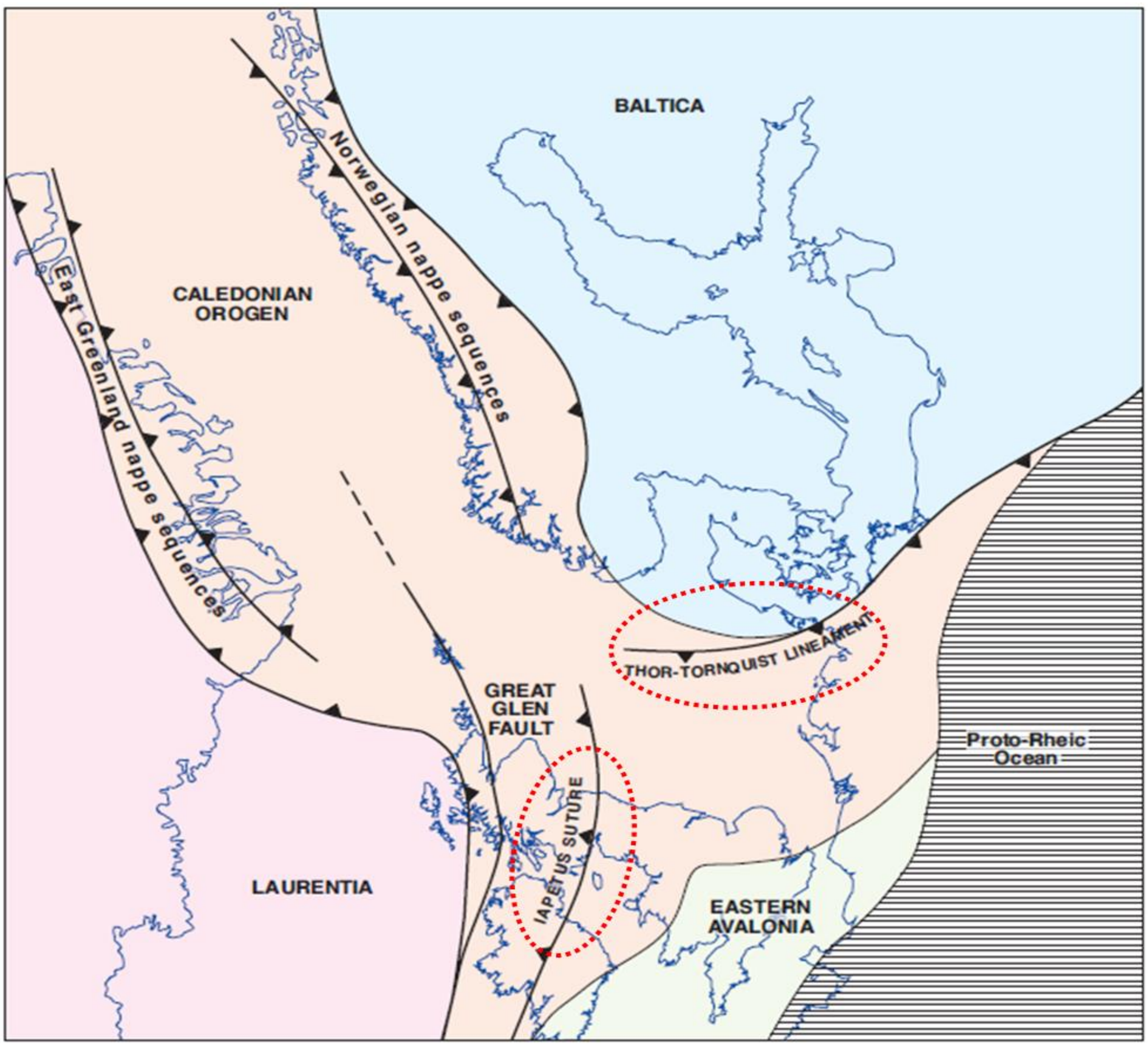


Figure 2.1: The suture zones formed by the collision are shown in red circles (Ziegler, 1982; cited and modified from Bassett, 2003).

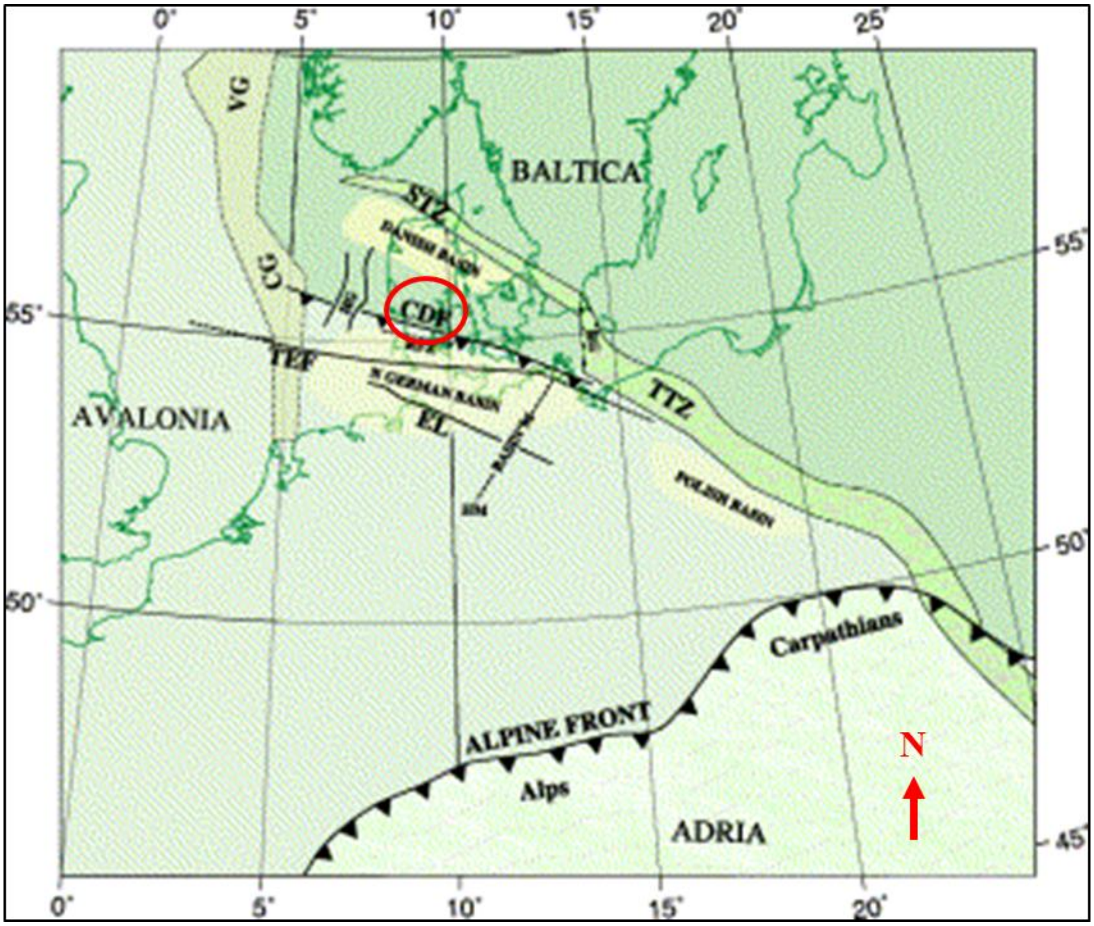


Figure 2.2: Caledonian Deformation Front is encircled in red, separating Baltic crust in the NE from the Avalonia crust in the SW (modified from Marotta and Sabadini, 2003).

2.1.2. Devonian tectonics history

After the build-up of the Caledonian Orogeny, the compressional regime changed to an extensional regime in the mid-Late Silurian. This caused sinistral strike-slip movements along several faults and the formation of small local basins (Marshall, 1991). During the Early Devonian the stress pattern changed regionally which caused further deformation (Soper et al., 1987). There was formation of a complex wrench fault system in mid-Devonian which was sub-parallel to the axis of the Arctic-North Atlantic Caledonides and the Appalachians. This included the Great Glen Fault (fig. 2.3) along which there was a sinistral strike-slip movement in the Devonian (Storedvedt, 1973). Further extension caused gravity collapse of the Caledonian structures to the north of the Highland Boundary Fault (fig. 2.3). This formed a series of half-grabens towards the north in between the Highland Boundary fault and the Møre-Trøndelag

Fault complex, which are major sinistral strike-slip faults (McClay et al., 1986; Norton et al., 1987; Seguret et al., 1989). In the mid-Devonian these small half graben structures formed the Orcadian Basin. This is one of the major Devonian basins in the NW Europe. The post-orogenic uplift with transcurrent faulting caused the rapid subsidence of the Midland Valley Graben (fig. 2.3) and the Orcadian Basin. The northern and southern Scottish Highlands were formed due to the post- Caledonian tectonic activities, which involved the strike-slip movement along the Great Glen fault (Ziegler, 1978).

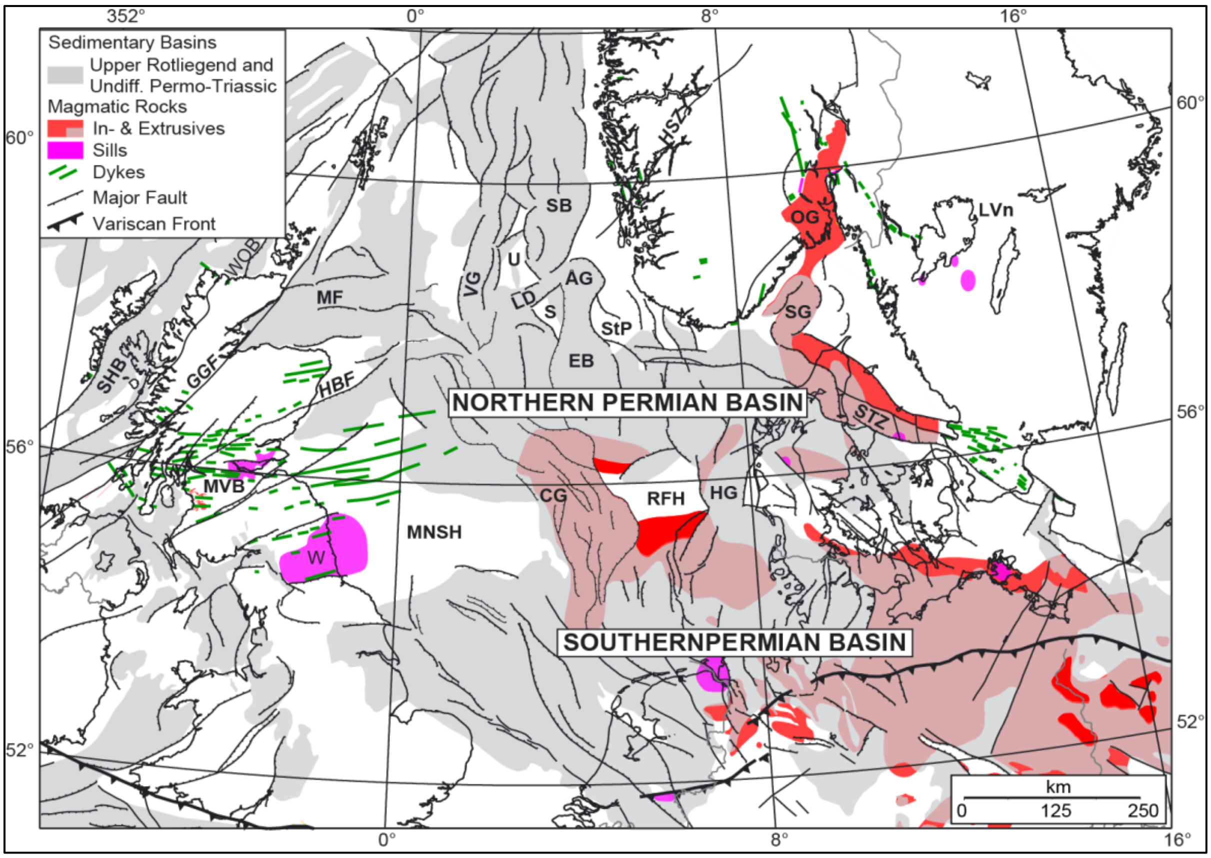


Figure 2.3: Regional geological map showing the main structural elements of the North Sea. The two Permian basins (Northern and Southern Permian basins) formed during the Early Permian subsidence. HSZ=Hardangerfjord Shear Zone, MF=Moray Firth Basin, MNSH=Mid-North Sea High, RFH=Ringkøbing-Fyn High, LD=Ling Depression, U=Utsira High, S=Sele High, SB=Stord Basin, VK=Viking Graben, AG=Åsta Graben, EB=Egersund Basin, HBF=Highland Boundary Fault, MVB=Midland Valley Basin, StP=Stavanger Platform, CG=Central Graben, HG=Horn Graben, GGF=Great Glen Fault, STZ=Sorgenfrei Tornquist Zone, OG=Oslo Graben and SG=Skagerrak Graben (Heeremans and Faleide, 2004).

2.1.2.1. Devonian history of the Basement Shear Zones

Fossen (1992) divided the post-Caledonian extensional events of the Devonian into two different modes, i.e. Mode I and Mode II (fig. 2.4). These extension phases caused collapse of the Caledonian Orogeny and development of oblique extensional shear zones. During Mode I, there was back-sliding of the Caledonian nappes over the Baltic plate along the major décollement zone. This further resulted in the development of the NW dipping extensional shear zones such as Hardangerfjord Shear Zone and Nordfjord-Sogn Detachment (NSD) in Mode II (fig. 2.4). The extension occurred along a NW-SE direction, hence producing shear zones with a NE-SW lateral orientation. Further continuity of this ductile shear zone (Hardangerfjord Shear Zone) into brittle crust caused the formation of brittle faulting. This resulted in the development of the Lærdal-Gjende fault system in the Late Devonian age (Schærer, 1980 cited from Fossen and Hurich, 2005). This brittle fault system is represented as the continuity of the Hardangerfjord Shear Zone. The SW trend of the Hardangerfjord Shear Zone into offshore of the Norwegian North Sea area is followed by the Ling Depression. In the UK side of the North Sea area, the Highland Boundary fault probably links with the Hardangerfjord Shear Zone towards the NE (Fossen, 2010).

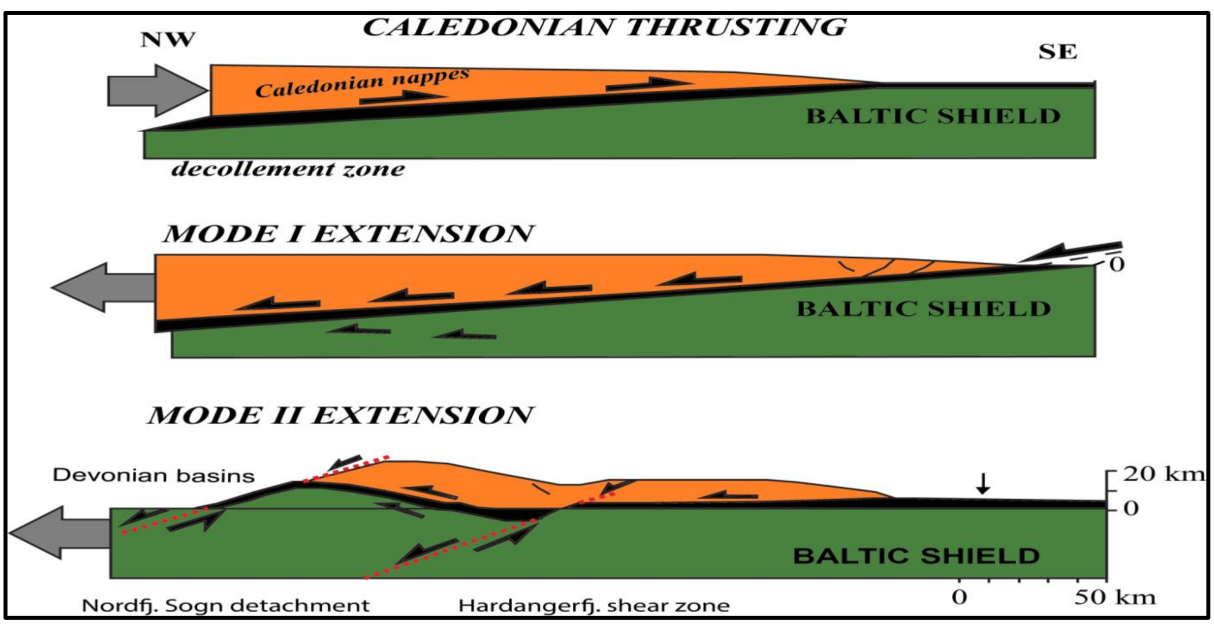


Figure 2.4: Schematic development of the Caledonian wedge and the large detachment zones including NSD and Hardangerfjord Shear Zone. Scale is shown at the lower right corner (modified from Fossen,1992).

2.1.3. The Variscan Orogeny and the Carboniferous tectonic history

In the Late Devonian and the early Carboniferous, Gondwana collided with the southern part of Laurussia, which resulted in the formation of the Variscan Orogeny. This collision also developed one large continent called Pangaea (Murphy and Nance, 2008). During the Carboniferous some major basins, like the Midland Valley Basin (fig. 2.3), started to subside more rapidly (Ziegler, 1978). The major NE-SW trending faults were formed during the Devonian-early Carboniferous times (Ziegler, 1978). In the late Carboniferous, crustal thickening due to the Variscan Orogeny resulted into orogenic collapse (Burg et al., 1994; Rey et al., 1997). This further resulted in crustal thinning across Central and Western Europe. The late Carboniferous events caused thermal destabilization and stretching of the crust which resulted in volcanic activity in wide areas including the Oslo Graben, the Skagerrak Graben (see fig. 2.3), Germany and the northern England (Bruce and Stemmerik, 2003; Heeremans and Faleide, 2004).

2.1.4. Permian tectonics

During the Late Carboniferous-Early Permian, magmatic and lithospheric stretching activity resulted in extensional basins. Rifting commenced during the Early Permian resulting in N-S oriented faults and generated two major sedimentary basins (Ziegler, 1982. 1990; Glennie, 1998; Van Wees et al., 2000; Frederiksen et al., 2001; Glennie et al., 2003; Neumann et al., 2003) in the North Sea, which are the Northern Permian Basin and the Southern Permian Basin (fig. 2.3).

The Northern Permian Basin extends from the Moray Firth Basin in the west to Bornholm in the east and the Southern Permian Basin extends laterally from Poland to England. It covers the foreland basin formed during the Variscan Orogeny. The Northern Permian Basin is separated from the Southern Permian Basin by the two highs which are the Mid-North Sea High and the Ringkøbing-Fyn High (fig. 2.3). The two highs were formed during the Late Carboniferous-Early Permian period (Ziegler, 1978; Javed, 2012).

These two basins have E-W lateral extent. During the Early Permian, Rotliegend clastic sediments were deposited within the basins, which were derived from the collapsing Variscan orogeny (Glennie, 1972). The increase subsidence rates resulted in the formation of large topographic depression. Further onwards, continuation of the rifting and the rise in the global sea-level caused the Zechstein seas to transgress into the Southern and Northern Permian Basins

(Birkelund and Perch-Nielsen, 1976). During the Late Permian period, the area experienced arid climatic conditions, which with the periodic global sea level changes resulted in the cyclic deposition of the Zechstein salts in these Permian basins (Ziegler, 1978).

2.1.5. Tectonic events in the Mesozoic period

During the Triassic, basins formed in the Early Permian continued to subside more which caused thick accumulation of the Triassic deposits. This further triggered the salt movement during mid-Late Triassic.

In the Early Jurassic, uplift in the central North Sea area caused thermal doming (Ziegler, 1982, 1988). This dome has a lateral extent reaching from the Southern Viking Graben in the north to the southern North Sea. In addition, a large volcanic complex developed at the site of a triple junction (Southern Viking Graben, Moray Firth Basin and Central graben) in the North Sea (see fig. 2.3; Ziegler, 1990). During the mid-Jurassic, volcanic activity ceased in the Central North Sea, which further caused the regional subsidence of the Central North Sea Dome. This regional subsidence resulted in a transgression, which established the deep water conditions in the Viking and Central Grabens. Highly organic rich shales of the Upper Jurassic were deposited in these marine environments in the Central and the Northern North Sea (Ziegler, 1978).

The North Sea underwent a major rifting event in the Late Jurassic. This rifting event was later followed by inversion in the Late Cretaceous-Early Cenozoic (Lyngsie et al., 2006). The Late Jurassic rifting resulted in the formation of NNE-SSW trending graben structures and some basement highs (Ziegler, 1978). The key structural features which came into existence during the Jurassic rifting are the Viking-Central graben system in the Northern North Sea and the Central North Sea respectively (fig. 2.3; Ziegler, 1975). The Central Graben transected the Mid North Sea High and the Ringkøbing-Fyn High (Ziegler, 1978). The Central Graben further intersects with the Horn Graben in the Southern North Sea (fig. 2.3; Heybroek, 1974, 1975).

The relative drop in the sea-level occurred during the Early Cretaceous. This helped to develop the Base Cretaceous unconformity (Rawson and Riley, 1982).The Late Cretaceous stage is characterized by the inversion and deformation in the North Sea due the compressional stresses caused by the Alpine Orogeny (Lyngsie et al., 2006). This resulted in the formation of large anticlines and monoclines in the North Sea. The salt tectonics also remained active during the Cenozoic period (Stewart et al., 1994).

2.2. Regional stratigraphic framework

The regional stratigraphy of the North Sea is as follows:

2.2.1. Devonian stratigraphy

The stratigraphy of the Devonian consists of lacustrine deposits, primarily shales and sandstones. During the Early Devonian period most of the sedimentary processes were of alluvial, aeolian and lacustrine origin. In the Late Devonian, sedimentation was controlled by fluvial processes. The Devonian Old Red sandstone facies were widely deposited in the North Sea area. In some places in the Central and Northern North Sea, these sandstones are eroded, as many wells have encountered basement without encountering the red beds of the Devonian (Marshall and Hewett, 2003).

2.2.1.1. Lower Old Red group

The base of this group is marked by an angular unconformity. It was deposited in different tectonic settings considering uplift and erosion during the Caledonian Orogeny. This group consists of volcanic rocks with minor sandstone and conglomerate intercalations (Marshall and Hewett, 2003). This group has been encountered onshore in the Midland Valley of Scotland (Armstrong and Paterson, 1970; Cameron and Stephenson, 1985; Haughton and Bluck, 1988). It is supposed to be thin or absent in the central North Sea **(**Marshall and Hewett, 2003).

2.2.1.2. Middle Old Red group

The transition from the lower to the middle Old Red group is marked at a point where the footwalls of individual half-grabens were covered by sediments and finally created the Orcadian Basin. This basin is located approximately at the same place as the Moray Firth Basin (see fig. 2.3). This group dominates in the Orcadian Basin and the surrounding offshore areas (Marshall and Hewett, 2003). It also consists of sandstones, shales, conglomerates and some marl.

2.2.1.3. Upper Old Red group

This group was deposited in the mid-Late Devonian. At this time there was a thorough drainage system within the basins. It consists of mostly sandstones which are of fluvial origin. It is widely distributed across the North Sea. The extent of these sandstones is from the Orcadian Basin upto the offshore areas along the Highland-Boundary Fault and Mid-North Sea High (Marshall and Hewett, 2003).

2.2.2. Carboniferous stratigraphy

The sandstones of fluvial origin were deposited during the Late Devonian to early Carboniferous time. During Carboniferous times climate had changed from arid to more humid due to which the depositional environment changed to marine.

During the Late Carboniferous, there was volcanic activity which was widespread in NW Europe (Heeremans et al., 2004b). Coal was deposited in the Southern North Sea during the Late Carboniferous, which is the main source for gas. But the absence of the Upper Carboniferous coal in the Central and Northern North Sea makes the Upper Carboniferous deposits economically less important in this area (Bruce and Stemmerik, 2003).

2.2.3. Permian stratigraphy

The Permian stratigraphy is divided into two major groups which are the Rotliegendes and the Zechstein groups (fig. 2.5). The Rotliegendes group was deposited during the Early Permian. Its lower part consists of volcanic rocks followed by continental clastics in the upper part (fig. 2.5). The clastics succession consists of shales, clays and sandstones with minor intercalations of conglomerates. They are mostly formed by recycled Devonian strata, due to which the sediments are red and devoid of fossils. So in some areas where the Carboniferous is missing, it is very difficult to differentiate between the Devonian and the Lower Permian Rotliegend clastics.

The Zechstein Group is of Late Permian age and has variable thickness (Glennie et al., 2003). The Zechstein unit consists of evaporites (i.e. halite and anhydrite) and dolomite. The salt often forms salt diapirs and salt domes which created several structural hydrocarbon traps in the North Sea (Glennie, 1998). During this period the Southern and Northern Permian Basins (see fig. 2.3) got flooded probably due to melting of the Gondwanan ice sheets. The desert climate during the

Late Permian caused evaporation and finally deposition of these massive evaporite deposits of the Zechstein group. This occurred in 3 to 4 cycles in both the Northern and Southern Permian Basins (Glennie et al., 2003).

2.2.4. Triassic stratigraphy

In the Central North Sea, the Triassic stratigraphy consists of the Smith Bank formation and the Skagerrak formation (fig. 2.5). The Smith Bank formation is of Lower Triassic age and consists of clay stones with minor sandstone intercalations. It also consists of conglomerate, dark shales, limestone and dolomite in some parts of the North Sea area. The Skagerrak formation of Late Triassic age overlies the claystone sequences of the Smith Bank formation. This formation mostly consists of sandstones, conglomerates with minor occurrences of shales and siltstones (see fig. 2.5; Deegan and Scull, 1977).

2.2.5. Jurassic stratigraphy

There are several unconformities in the Jurassic period which were the result of block faulting and erosion (fig. 2.5). The base of the mid-Jurassic mostly consists of deltaic sandstone sequences with minor shale and silt layers. The upper boundary of the upper Jurassic is marked by the Kimmeridge clay **(**Deegan and Scull, 1977**)**.

2.2.6. Cretaceous stratigraphy

The rifting event was active in the Late Jurassic and it influenced the sedimentation until some stages of the Early Cretaceous. But the rifting and tilting of blocks and graben structures was less effective on the Cretaceous sedimentation. The two groups related to the Cretaceous are the Cromer-Knoll Group and the Chalk Group **(**fig. 2.5; Deegan and Scull, 1977**)**. The Chalk Group of Upper Cretaceous age is more widely distributed in the North Sea than the Lower Cretaceous Cromer-Knoll Group (Ziegler, 1975).

2.3. Structural elements

The main structural features related to the study area (fig. 2.6) are as follows

2.3.1. Hardangerfjord Shear Zone

The first large-scale post-Caledonian extensional structure to be discovered was the NE-SW trending ductile, syn-formal type depression which was named the Faltungsgraben (Goldschmidt, 1912 cited from Fossen and Hurich, 2005). It is located in the Central South Norway. It was later referred to the Hardangerfjord Shear Zone (Fossen, 1992). This large-scale structure is characterized by both folding and faulting. On the east of the Hardangerfjord Shear Zone there are thin sub-horizontal basement nappes. Then within the segment of the Hardangerfjord Shear Zone and on its eastern flanks the Fennoscandian basement and also nappes are bending down into the syn-formal depression. On the western side of the Hardangerfjord Shear Zone, the Caledonian nappes and the underlying gneiss region form a contact zone which is dipping towards the east and the thickness of the nappes towards west is larger as compared to the east of the Hardangerfjord Shear Zone (Andersen, 1998).

On land, the Hardangerfjord Shear Zone can be easily traced towards the NE. Its length is about 350 km which is determined from the Hardangerfjorden area, passing through the Aurland area and up to the Vågå area. Further towards the NE on land, the Hardangerfjord Shear Zone cannot be traced because it is hidden under the brittle Lærdal-Gjende Fault Zone (Fossen and Hurich, 2005). Into offshore area towards the SW, this Lineament falls along the trend of the Ling Depression (fig. 2.6) (Færseth et al., 1995a). This Lineament indicates that there is a weak zone which is more than 1000 km long and it is also very deep into the North Sea. The weak zone has affected this area of the North Sea and also the trend and orientation of the faults (Fossen and Hurich, 2005).

2.3.2. Ling Depression

The Ling depression is of great importance because of its unique orientation and complexities in its fault patterns, probably representing different tectonic regimes. This area can provide in-depth understanding of the development of the Northern Permian basin in the Late Paleozoic era (Heeremans and Faleide, 2004).

The Ling Depression falls on the trend of the NE-SW trending Hardangerfjord Shear Zone (fig. 2.6) and the Lærdal-Gjende Fault zone. The N-S trending normal faults cross cut the area around the Ling Depression which are supposed to be related to the Permo-Triassic and the Jurassic rifting stages. The Ling Depression also separates the two adjacent highs which includes the Utsira High to the North and the Sele High to the South. The Ling Depression and the Åsta graben mark the northern limit for the Permian Salt Basin (Heeremans and Faleide, 2004).

2.3.3. Utsira High

The Utsira High is a basement high with the Ling Depression located on its southern flank, the Viking Graben on the west and the Stord Basin towards the east as shown in figure 2.6. Its lateral extent is along N-S striking faults which were probably formed during the Late Carboniferous rifting stage.

2.3.4. Sele High

The Sele High is a dominantly granite-cored paleo-high (Bartholomew et al., 1993). It is bounded by faults on all sides in such a way that it forms a triangular shape high (fig. 2.6). The Ling depression lies towards its north, the Norwegian-Danish Basin is on the western side and the Åsta Graben and the Egersund Basin are located on the eastern side.

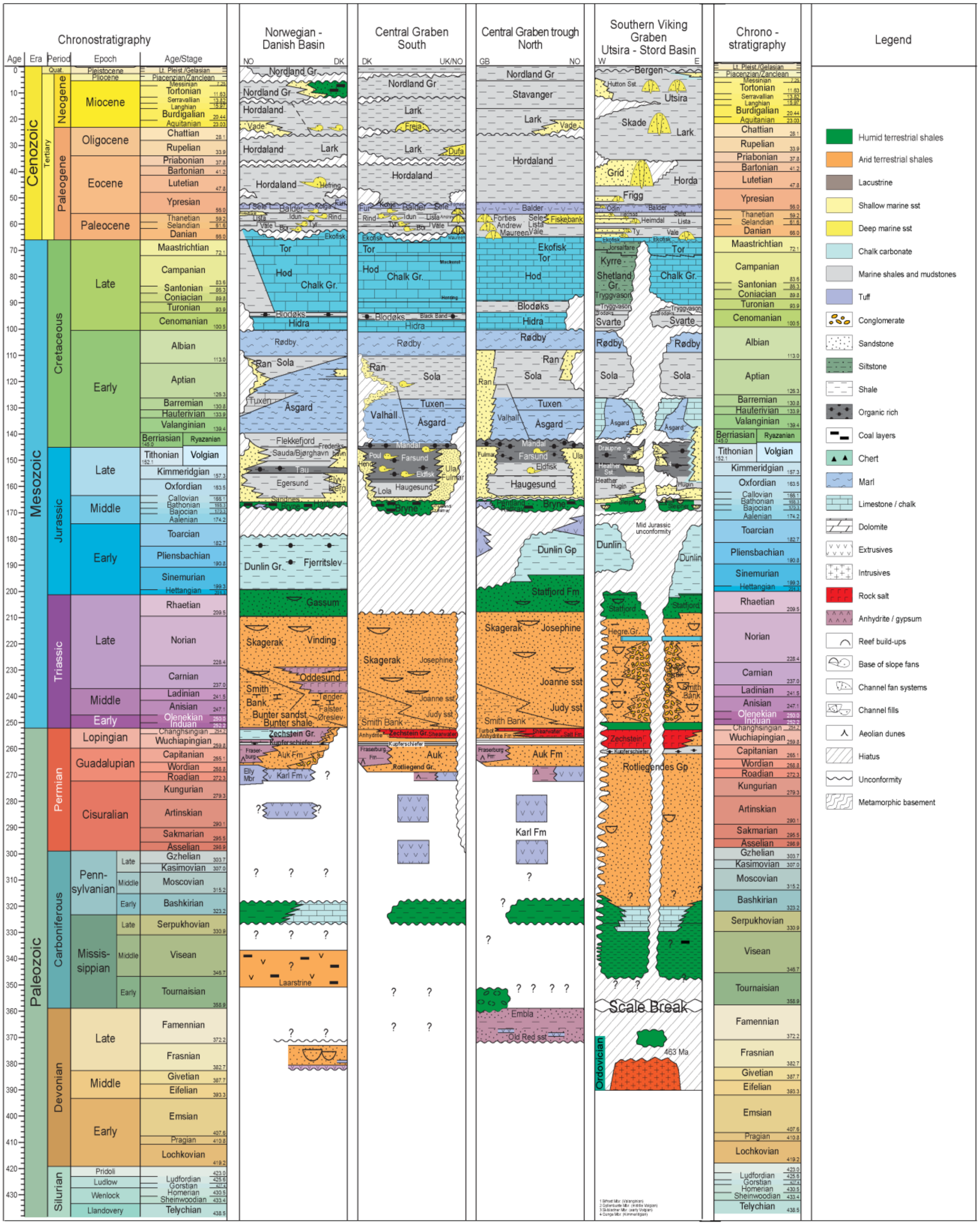


Figure 2.5: A chart showing standard lithostratigraphy of the Offshore Norway (Gradstein et al., 2012; NORLEX project).

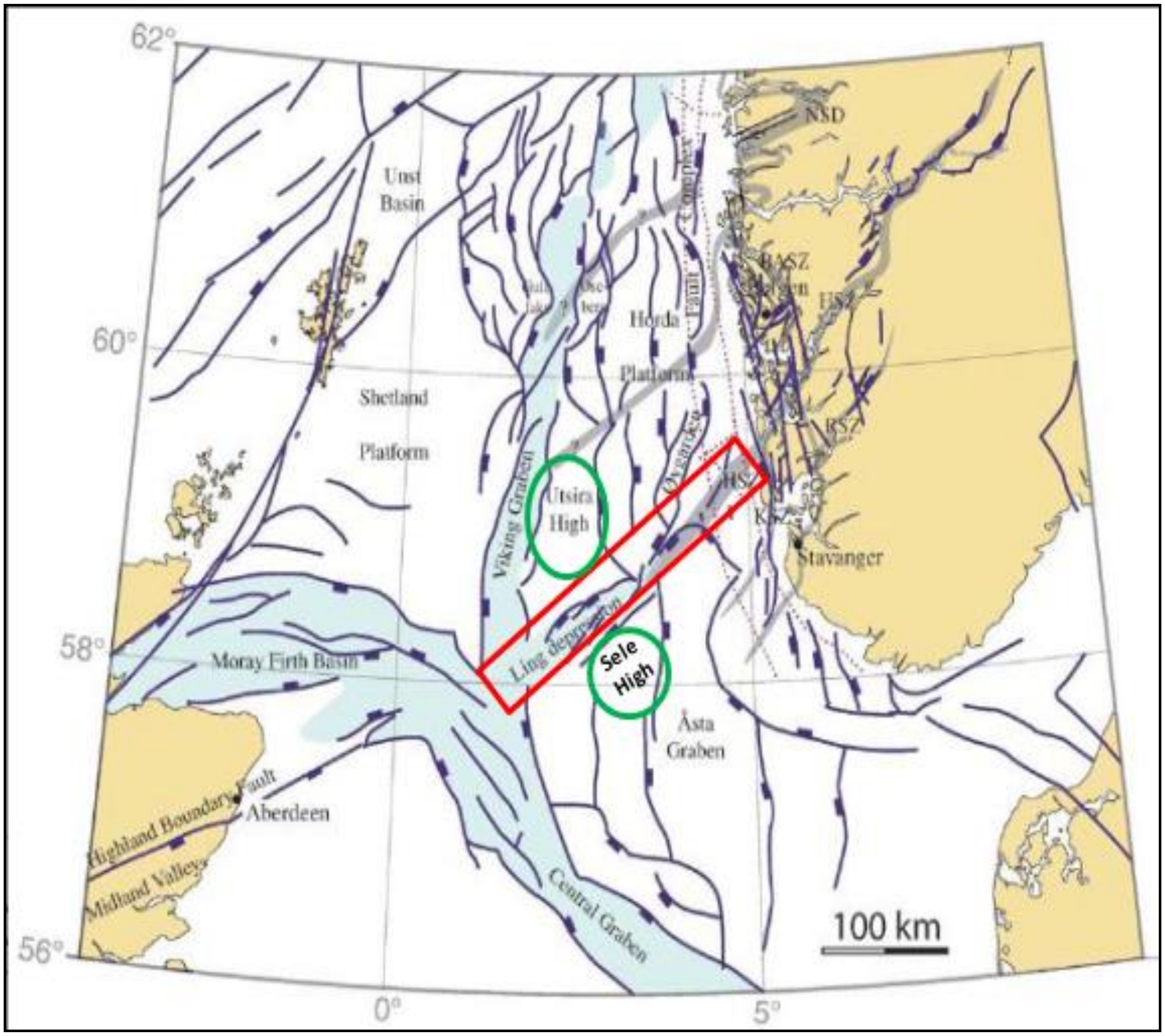


Figure 2.6: Regional map of the North Sea showing the key structural features related to the study (Hardangerfjord Shear Zone, Ling depression, Utsira High and Sele High). The trend of the Ling Depression with respect to the Hardangerfjord Shear Zone is shown in red rectangle (Ziegler, 1990; Færseth, 1996; cited and modified from Fossen and Hurich, 2005).

CHAPTER 3

DATA AND METHODOLOGY

3.1. Introduction

Figure 3.1 shows the main work flow which was used in the study. The main purpose was to determine the structural and geological evolution of the Ling Depression and its adjacent highs.

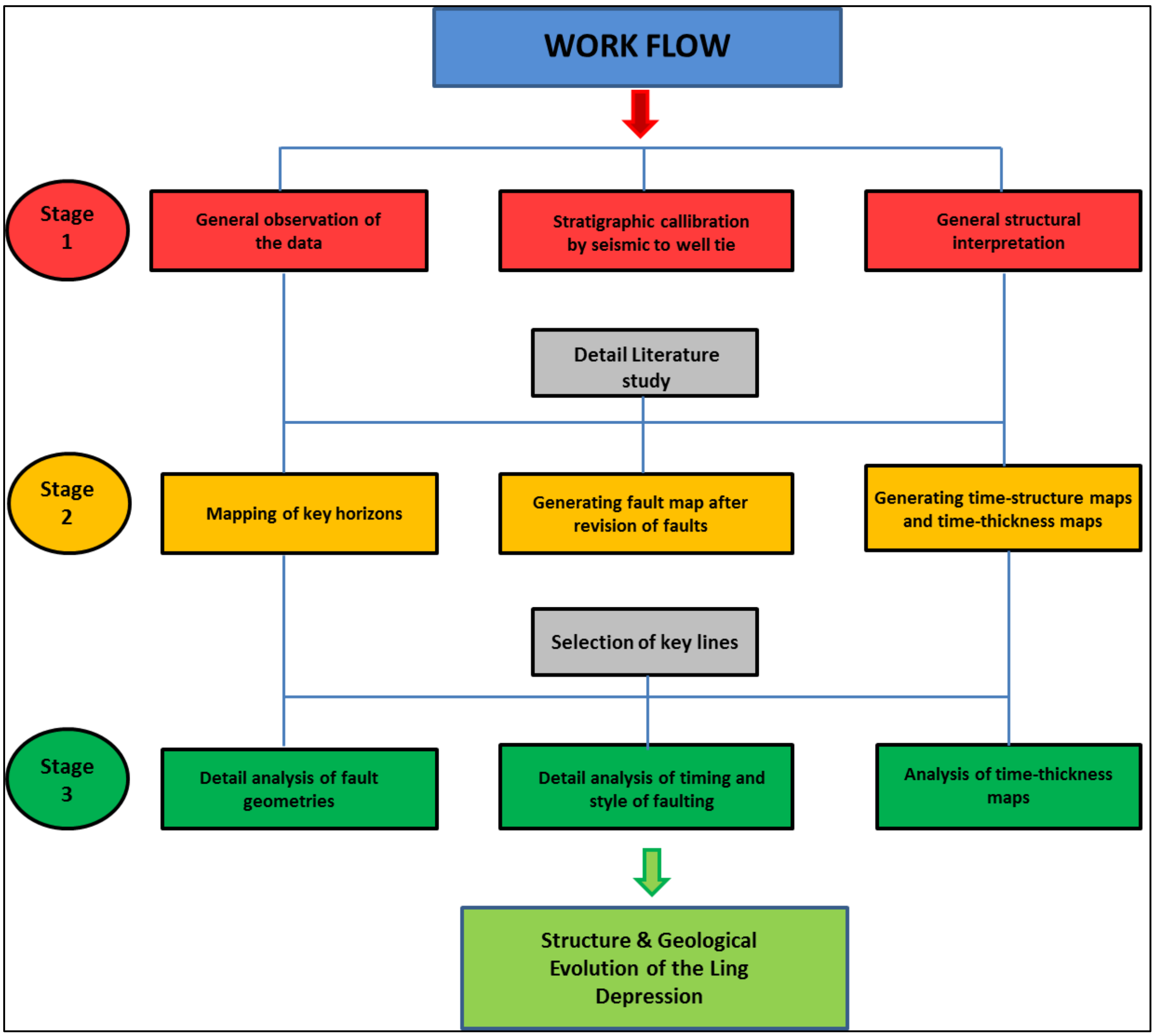


Figure 3.1: The main work flow pattern adopted to determine the structure and geological evolution of the Ling depression. This includes three different stages.

3.2. Data

The data which were available for this study includes:

- Regional 2-D seismic profiles.
- Well data.

3.2.1. Regional 2-D seismic profiles

There were a total of four seismic surveys used during this study. From the four 2-D seismic surveys, suitable seismic lines were selected which covered almost all the study area including the Ling Depression, the Sele High and the Utsira High (fig. 3.2). The main focus during the interpretation of these seismic lines was on the Ling Depression and the Sele High. Seven key seismic profiles were selected (fig. 3.2) which cross-cut the main structural geometries and provided maximum detail on key structural features.

3.2.2. Well data

Well data included the deviation files and the check shots for thirteen different wells (fig. 3.2). Initially borehole data of all thirteen wells were used for stratigraphic calibration through well to seismic ties. For this purpose all the details of the wells were taken from the webpage of Norwegian Petroleum Directorate (npd.no). 8 wells are drilled on the Utsira High and most of them penetrated into the basement. The stratigraphy encountered during drilling gives evidence that Permian strata are not present or has been eroded on the Utsira High. Even in some wells, the Triassic is also missing and the basement was encountered after the Jurassic or the Cretaceous strata. Most of the wells were only helpful in getting stratigraphic control on the Base Chalk horizon which was the reference horizon in this study. Thus, out of thirteen wells, detail information of only seven wells is given in the table 3.1. Wells 16/6-1 and 16/5-1 are located on the Utsira High. Wells 16/8-1, 16/8-2 and 17/4-1 are located in the Ling Depression. The remaining two wells, 17/12-2 and 17/11-1, are located in the Egersund Basin (SE flank of Sele High) and on the Sele High respectively (fig. 3.2). From the given data in table 3.1 both wells located on the Utsira High penetrated the basement. The legend for the color pattern in table 3.1 is shown in table 3.2 along with their ages.

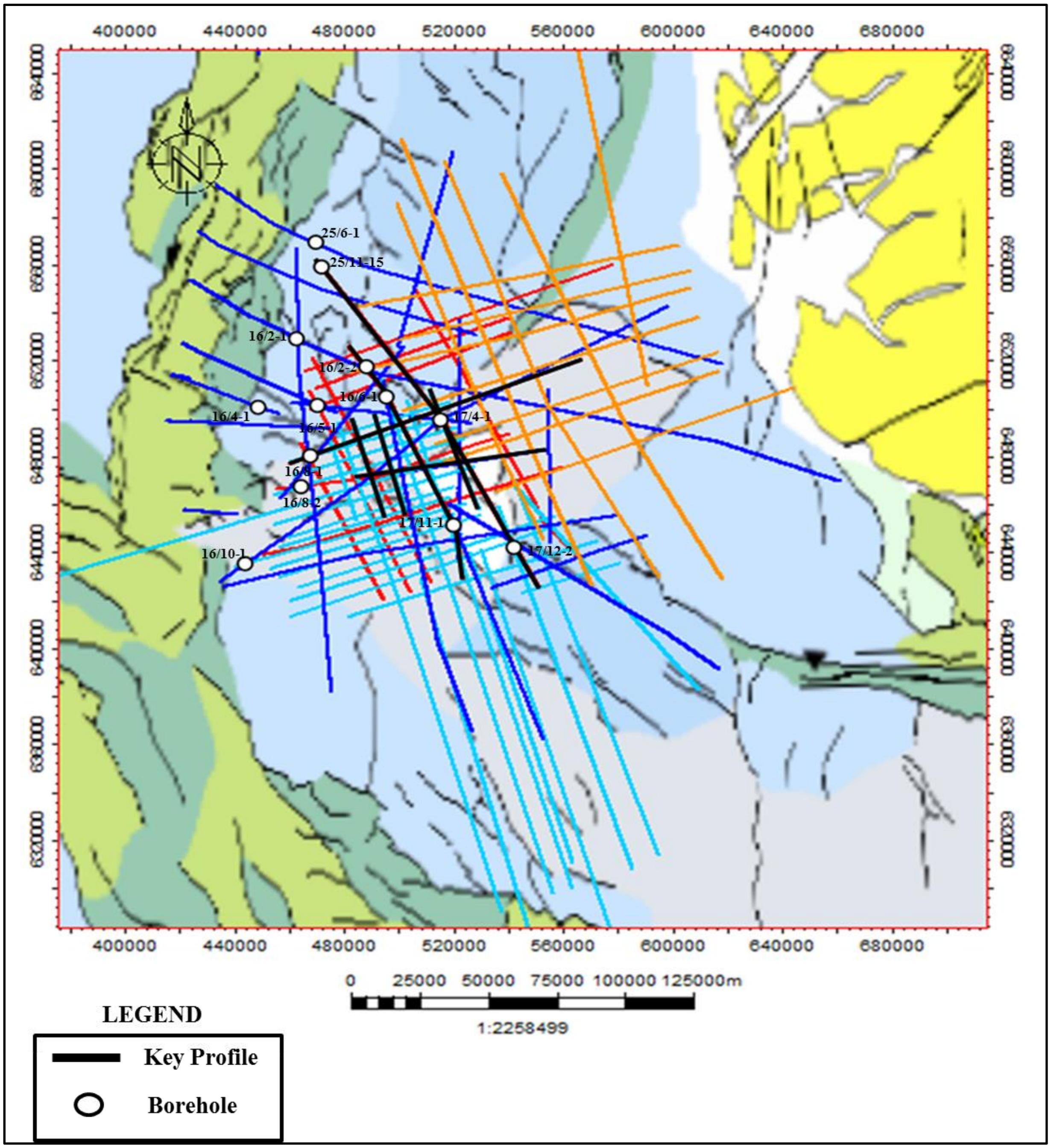


Figure 3.2: Base map of study area showing the four 2-D seismic surveys displayed in different colors. Bold black lines are the key profiles used for detailed structural and stratigraphic analysis.

AGE	Group/Formation	16/6-1 MD	16/5-1 MD	16/8-1 MD	16/8-2 MD	17/4-1 MD	17/12-2 MD	17/11-1 MD
CENOZOIC	NORDLAND GP	145	127	106	103	132	93	102
	UTSIRA FM	722	754	765	815			
	HORDALAND GP	769	1012	955	975	544	707	600
	ROGALAND GP	1255	1527	1568	1525	1041	924	967
	BALDER FM	1255	1527	1568	1525	1041	924	967
	SELE FM	1292	1557	1608	1571	1080	951	990
	LISTA FM	1307	1580	1650	1625	1108	957	1005
	MAUREEN FM						987	
	VÅLE FM	1335	1648	1740	1752	1150		
LATE CRETACEOUS	SHETLAND GP	1344	1662	1750	1763	1163	991	1020
	EKOFISK FM	1344	1662	1750	1763			1020
	TOR FM	1362	1699	1775	1795	1163		1040
	HOD FM	1548	1756	1791	1850	1370		1361
	BLODØKS FM	1654				1408		
	SVARTE FM	1734	1848					
	HIDRA FM					1438		
EARLY CRETACEOUS	CROMER KNOLL GP	1771	1859	1829	1900	1444	1476	1447
	RØDBY FM	1771		1829	1900	1444		1510
	SOLA FM	1894	1859	1879	1945			1587
	TUXEN FM							1665
	ÅSGARD FM	1925	1923	1900	1972	1706		1724
	MIME FM					2080		
MID-LATE JURASSIC	BOKNFJORD GP						1932	2083
	VIKING GP	2019		2041	2187	2122		
	DRAUPNE FM	2019		2041	2187	2122		
	HEATHER FM				2238	2217		
	VESTLAND GP					2265	2157	
TRIASSIC	NO GROUP DEFINED		MISSING			2352		
	SKAGERRAK FM					2352		2211
	SMITH BANK FM			2116		2532		2315
LATE PERMIAN	ZECHSTEIN GP				2254	2665	2243	2517
	UNDIFFERENTIATED	MISSING		NOT PENETRATED	NOT PENETRATED	2665		NOT PENETRATED
	KUPFERSCHIEFER FM					3834		
EARLY PERMIAN	ROTLIEGEND GP					3834	2293	
PRE-PERMIAN	BASEMENT	2055	1925	NOT PENETRATED				

Table 3.1: The formations present in different wells which are used during the study. Color pattern calibrates with four different horizon interpreted for the study purpose. See table 3.2 for color pattern guide.

HORIZONS	GROUPS	AGE	COLOR PATTERN
Base Chalk	Shetland Group	Late Cretaceous	
Base Mid-Jurassic	Vestland Group	Mid-Jurassic	
Base Triassic	Smith bank Formation	Early Triassic	
Base Zechstein	Zechstein Group	Late Permian	

Table 3.2: Guide for the color pattern shown in table 3.1. These colors are related to different horizons interpreted during the study.

3.3. Interpretation method

Interpretation was carried out in three different stages as shown in figure 3.1. The interpretation software used during the study was Petrel 2012 by Schlumberger. Initially a basic literature study was carried out regarding the study area, to become familiar with the main structures. Then the general overview of the available data was conducted. This includes the observation of the 2-D seismic data and considering the well details. After conceiving the stratigraphy of different wells, measured depths of the four horizons were marked and loaded into Petrel. Well to seismic tie was performed to calibrate the well tops with the seismic data. Some major faults were interpreted before starting interpreting the horizons on the seismic sections. This led to the much better control on the horizon interpretation in later stages.

After well to seismic tie and interpreting major faults, a detailed study of the area was carried out and horizon interpretation was started. Initially horizons were picked by well 17/4-1 because of the strong reflections of the desired horizons and seismic image quality was also not distorted due to the salt halokinesis (fig. 3.3).The four horizons picked during the interpretation are:

- Base Chalk.
- Base Mid-Jurassic.
- Base Triassic (Top Salt).
- Base Zechstein (Base Salt).

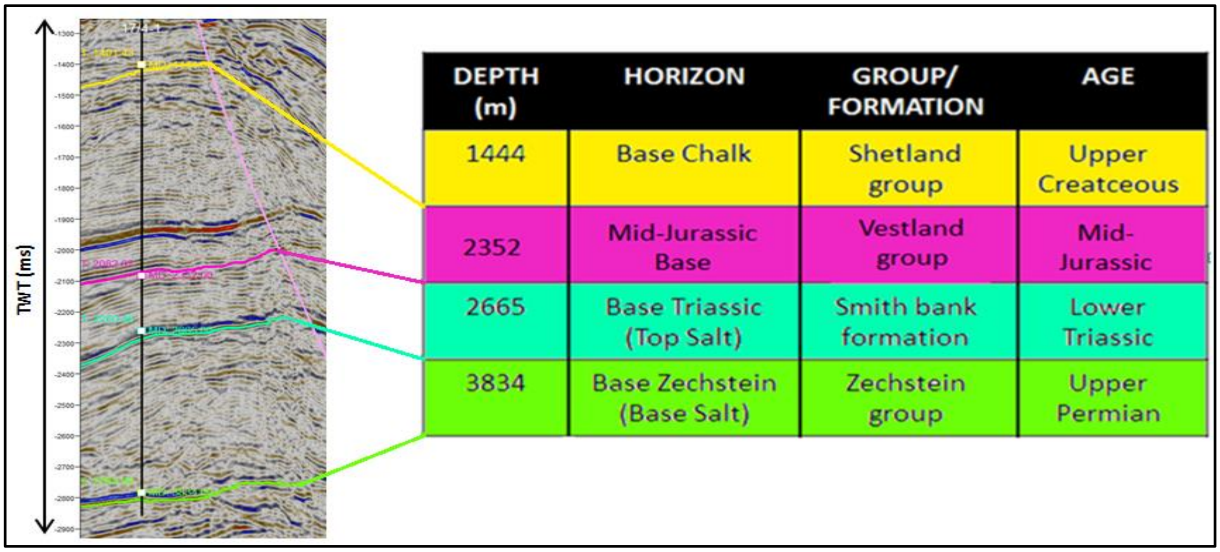


Figure 3.3: Well to seismic tie along well 17/4-1. It is showing the horizons interpretation in the Ling Depression.

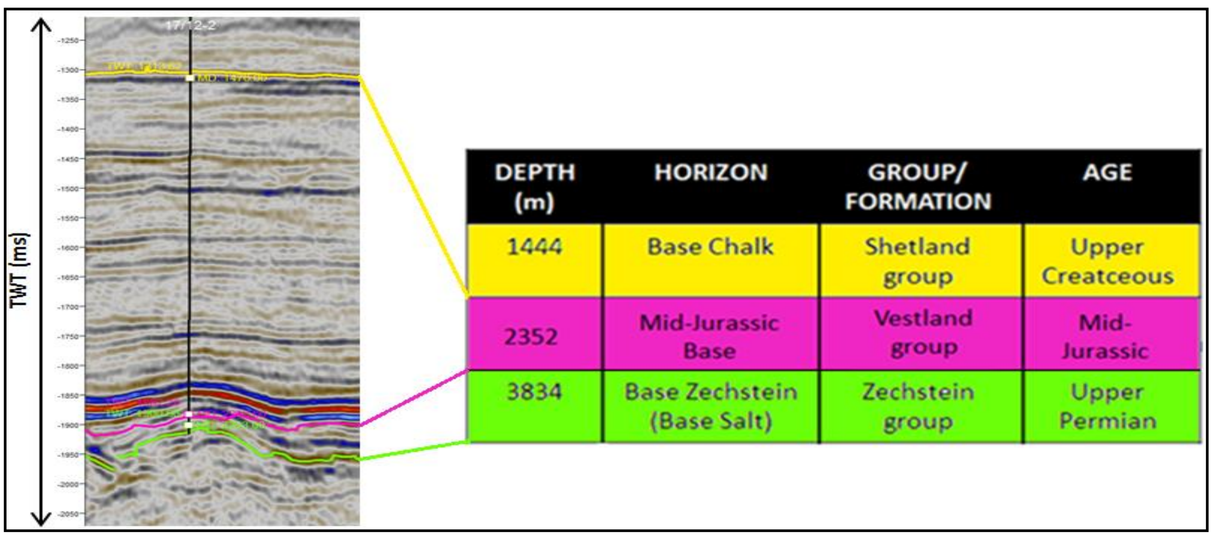


Figure 3.4: Well to seismic tie along well 17/12-2. It is showing the interpreted horizons on the SE flank of the Sele High. The Base Triassic is missing.

Horizons were first picked along the wells where the level of uncertainty was minimal due to well control. Later on they were picked on the entire data set of 2-D seismic lines with in the study area. Due to nice well control in the study area it was easy to mark the horizon around the wells, but there were some difficulties due the salt halokinesis. In some parts of the area salt is absent/eroded as shown in figure 3.4.

After picking the horizons on the entire data set, surfaces were generated which were used to make the time-structure maps. The fault maps were made by revising the interpretation of main faults and interpreting some more deep faults.

In the last stage, key seismic lines were selected. The key profiles were selected on the basis of their lateral extent covering mostly the study related structural elements and displaying maximum structural and stratigraphic features to determine the geological evolution of the study area. Most of the key lines are intersecting the Ling Depression, the Utsira High and the Sele High (fig. 3.2). Detailed analysis of the fault geometries was carried out on the key seismic lines, which further helped in understanding the timing and style of faulting. Analysis of time-thickness maps, time-structure maps and fault maps was further carried out to specify the lateral structural and stratigraphic variations throughout the study area. All together this detailed study helped in understanding the structure and evolution of the Ling Depression and its adjacent highs.

CHAPTER 4

SEISMIC INTERPRETATION AND RESULTS

4.1. Introduction

This chapter focuses on the details of stratigraphic and structural interpretation carried out on seismic key profiles. Seven regional profiles are selected for this purpose (fig.4.1). The key profiles cover all main structural elements related to the study area.

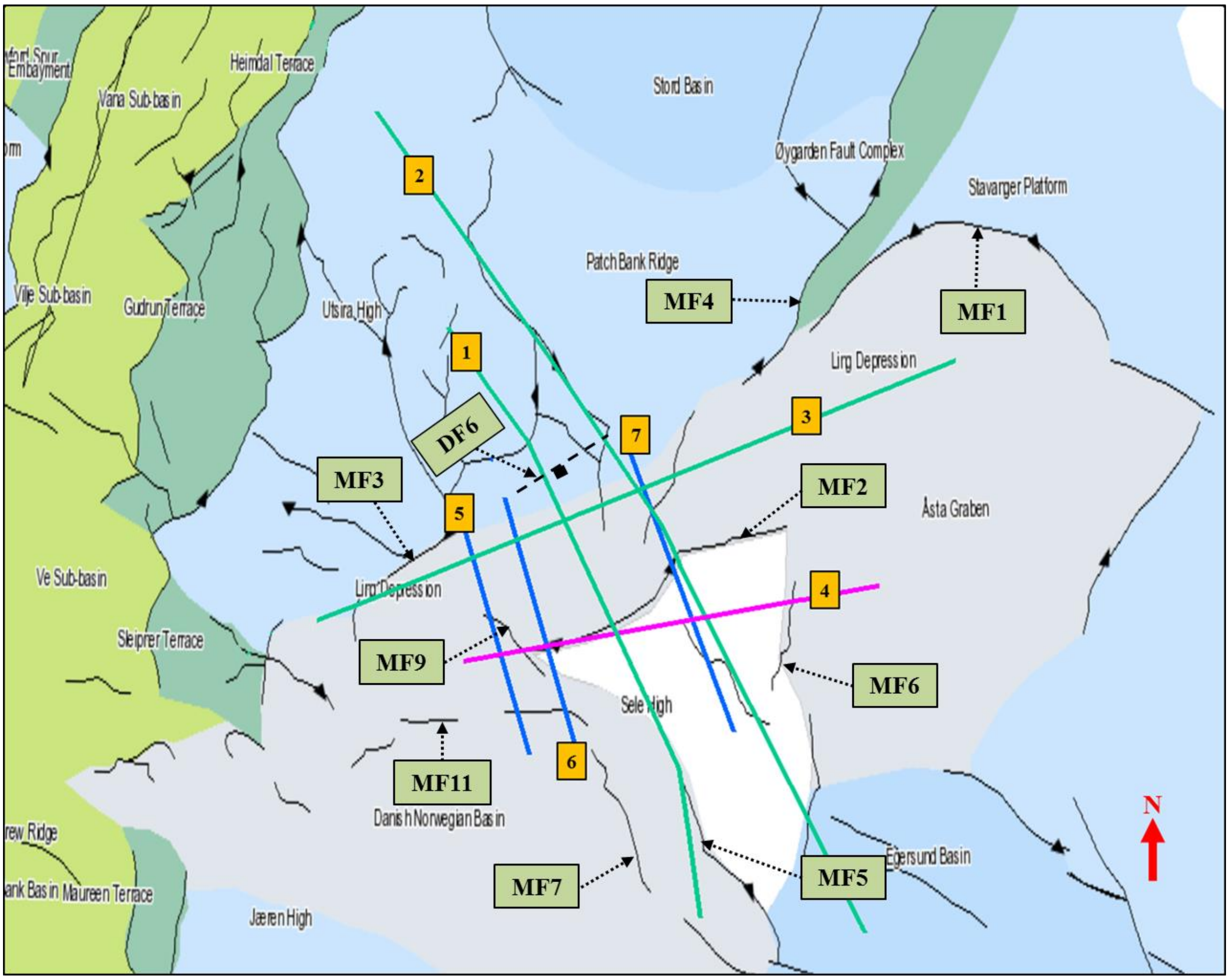


Figure 4.1: Location of regional key seismic profiles with their numeric order used for the study purpose. Name of the faults are also shown as they are used during this study (Note: DF6 was not present on this base map which is displayed by a dotted line) (npd.no).

4.2. Composite fault map

A composite fault map is created by correlating the fault maps of all the four different ages. The Color pattern of the faults is related to the color pattern given to the horizons at that certain stratigraphic level (see table 3.2). This composite fault map shows all the main faults covered in the study area. The main faults in this composite fault map are mostly the bounding faults of the main structural elements related to the study area. Ten main faults have been interpreted with some minor faults as shown in figure 4.2.

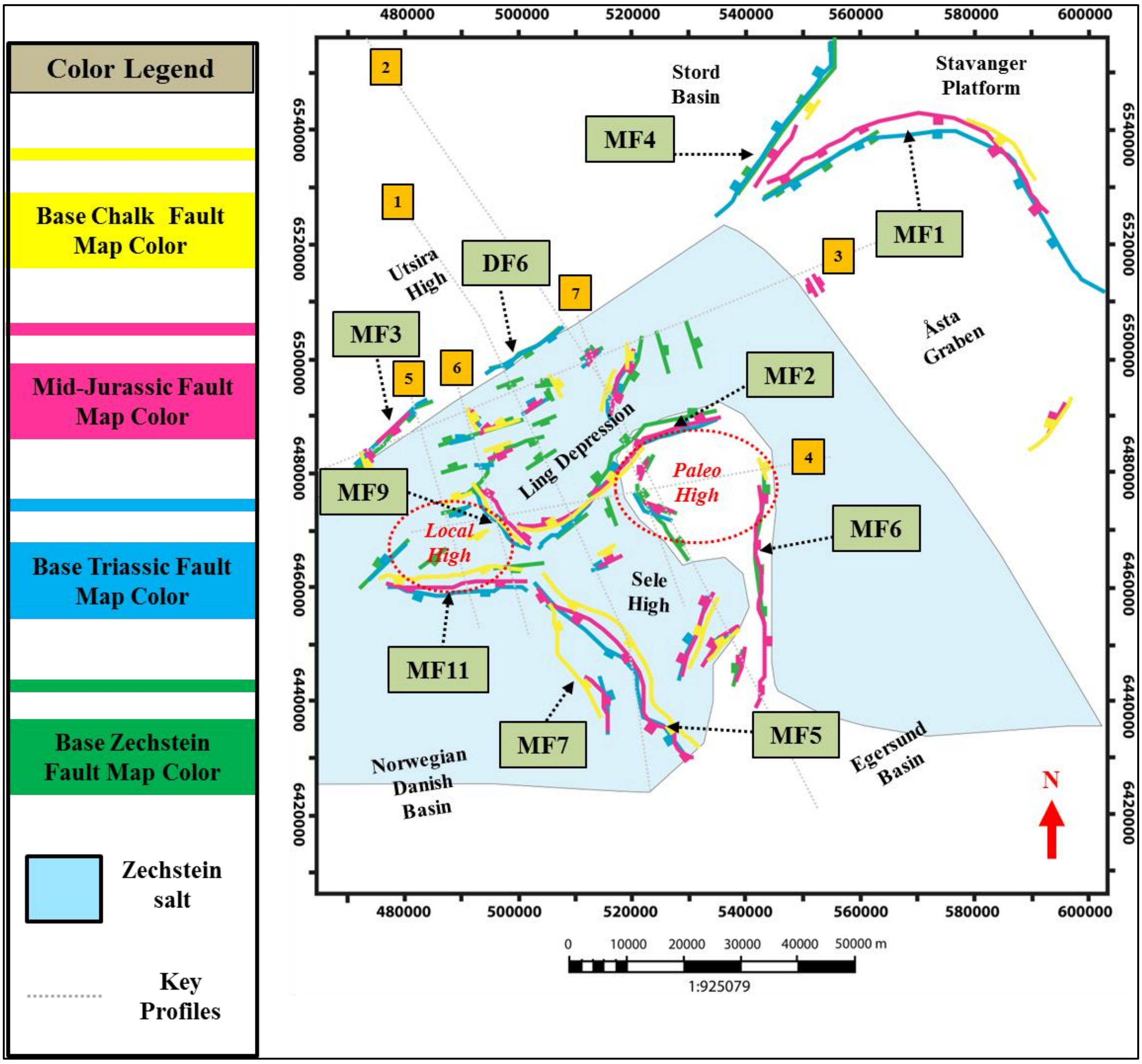


Figure 4.2: Composite fault map of the study area with all the main faults and some minor faults mostly interpreted on the key seismic profiles. The key profiles are identified by numeric order (see fig. 4.1). Color legend for the fault map is given on the left side. It is also showing the distribution of Zechstein salt in study area.

All the main faults in the study area are normal faults. The details of these faults are as follows:

4.2.1. MF1

The strike of this fault is WSW-ENE and changes to NW-SE. It is a large-scale fault bounding the NE part of the Åsta Graben and is located in the upper right corner of the study area (fig. 4.2). The dip direction along the WSW-ENE strike is towards the SE and as the strike changes to NW-SE it shows the SW dip direction. Towards north it is separating the Stavanger Platform and the Stord Basin from the Åsta Graben in south.

4.2.2. MF2

The strike of this main fault is from WSW-ENE. This fault is a bounding fault of the Sele High. Together with MF6 and MF5 they form a triangular shape of the Sele High (fig. 4.2). Its dip direction is towards the NW. This fault separates the Sele High from the Ling Depression.

4.2.3. MF3

Strike direction of this main fault is from the NE-SW (fig. 4.2). It is also a bounding fault of the Utsira High in the north. It is separating the Ling Depression from the Utsira High. The dip direction of this fault is towards SE.

4.2.4. MF4

This fault is related to the Øygarden Fault Zone. The fault segments related to this zone have maximum throw upto 5 km and they mark the eastern boundary of the Early Permian rift stage (Bøe et al., 2010). The strike of this fault is SSW-NNE and is located in the upper right corner of the study area (fig. 4.2). This fault has NW dip direction. It is separating the Stavanger Platform in the SE from the Stord Basin in the NW.

4.2.5. MF5

This main fault is striking NW-SE. It is also a bounding fault of the Sele High (fig. 4.2). The dip direction of this fault is towards SW. It covers the entire western part of the Sele High along the strike and separates the Sele High from the Norwegian-Danish Basin.

4.2.6. MF6

The strike of this main fault is N-S. It is almost located in the center of the study area and is a bounding fault of the Sele High (fig. 4.2). Its dip is towards the east. MF6 is separating the eastern part of the Sele High from the Åsta Graben and the Egersund Basin respectively.

4.2.7. MF7

It is a main fault with NW-SE strike direction. This fault is running parallel along MF5 but has opposite dip direction (fig. 4.2). It is not a bounding fault but is present in the Norwegian-Danish Basin. It has a NE dip direction and is present primarliy at the Base Chalk stratigraphic level.

4.2.8. MF9

This fault is crosscutting the lateral extent of the Ling Depression towards SW. Strike of this fault is NW-SE. It follows the same trend as MF5 but has opposite dip direction (fig. 4.1). It is not bounding any key structural element but it is forming an eastern boundary of a local high in the SW part of study area (fig. 4.2). It has a dip direction towards the NE.

4.2.9. MF11

This fault has an E-W strike direction. This fault separates the Ling Depression from the Norwegian-Danish Basin in the study area (fig. 4.2). It is also forming the southern boundary of a local high with respect to MF9 in SW part of study area (fig. 4.2). The dip direction of this fault is towards the south.

4.2.10. DF6

The strike of this main fault is from the NE-SW and it is located in the northwestern part of the study area (fig. 4.2). It is a deep fault cutting only upto the Base Triassic stratigraphic level. It is not present at the mid-Jurassic and the Upper Cretaceous stratigraphic levels. It runs deep down into the Paleozoic strata (see fig. 4.3.a). This fault together with MF3 is marking the northern boundary of the Ling Depression. It separates the Ling Depression in the south from the Utsira High in the north and has a dip direction towards the SE.

4.3. Description of key seismic profiles

There were several seismic profiles provided during this study. Seven key profiles have been selected further to be described in detail. The main reason for selecting them as the key profiles is because they are showing different structural features at different stratigraphic levels, which will help later in determining the structure and geological evolution of the Ling Depression and its adjacent highs. The detailed structural and stratigraphic analysis of the key profiles is carried out according to numeric order (fig. 4.1) which is as follows:

4.3.1. Key seismic profile 1

The key profile 1 has NW-S strike (fig. 4.1). This seismic line is located on the SE flank of the Utsira High and runs perpendicular to the central part of the Ling Depression, further this line cross cuts the NW flank of the Sele High and terminates in the Norwegian-Danish Basin (fig. 4.3.a). This profile highlights main structural elements in the study area including three major faults which are DF6, MF2 and MF5 (fig. 4.2).

DF6 is separating the Utsira High from the Ling Depression (fig. 4.3.a). This main fault cross cuts three deeper horizons related to this study and runs deep below into probably the Early Paleozoic stratigraphy. Its throw is almost 4500 ms TWT on the seismic section. There are several secondary faults present within the Ling Depression cutting the Late Permian level stratigraphy and running deep into the Early Paleozoic sedimentary rocks. These fault geometries form nice horst-graben structures probably during the Early to pre-Permian age. Moving further towards the south, main fault MF2 (fig. 4.3.a) is separating the Ling Depression from the Sele High. This fault segment is cutting the upper three key horizons of the study. It has an opposite dip direction to DF6 and together they form a fault set bounding the Ling Depression. Just beneath MF2, a fault is cutting the Base Zechstein horizon. It possibly is the continuation of MF2 but presence of the ductile salt layer makes it difficult to relate MF2 with this deeper level fault. Further down towards the south, into the Sele High, two opposing secondary faults are present at the Base Zechstein level and penetrating deep downwards. They are forming a big horst structure (Horst 1) on the Sele High (fig. 4.3.b). There are also some minor faults present at the shallower level of the study area on the Sele High. Moving more towards South along the seismic profile, a main fault MF5 (fig. 4.3.a) is encountered which is separating the Sele High from the Norwegian-Danish Basin. This fault was not completely mapped at deeper levels below the Base Chalk because of distortion in seismic due to salt movements. There are two more faults with opposite dip direction in the

Norwegian-Danish Basin area at the Base Zechstein (Late Permian) stratigraphic level. They are also forming a horst type structure (Horst 2) within the basin area (fig. 4.3.b).

Using data from three different wells, four different stratigraphic levels are interpreted on this seismic line. These are the key stratigraphic horizons related to this study (see table 3.2). Apart from the Base Chalk all other key stratigraphic horizons are missing on the Utsira High. According to the well data of 16/6-1 (see table 3.1), the Draupne Formation of the Mid-Jurassic age is sitting on top of the crystalline Basement of the Utsira High. The interpretation of the mid-Jurassic Horizon on the seismic profile was carried out by marking the base of the Vestland Group. Further towards the SE into the Ling Depression, all the four main horizons are present. These key horizons are also present on the NW flank of the Sele High but the mid-Jurassic horizon is missing further SE on this high (fig. 4.3.b). The top salt is also disturbed on the Sele High due to halokinesis. Towards the south, in the Norwegian-Danish Basin, the mid-Jurassic horizon is missing on top of Horst 2 (fig. 4.3.b) but further more towards the south, where this profile is terminating, we have all the four main horizons interpreted (fig. 4.3.b).

The Early to pre-Permian (pre-salt) stratigraphy is difficult to interpret because of the poor seismic quality at greater depths. Minor interpretation of probably the Lower Permian strata is done in the Ling Depression (fig. 4.4). We can observe the tilted strata below the Base Zechstein of the Late Permian age, which is lying straight on top of it, representing a possible unconformity. This tilted stratigraphy is due the listric nature of faults, which have resulted in the tilted/rotated fault blocks. These may be possible Rotliegend half-grabens present deep below in the Ling Depression. This can be assumed on the basis of the details of 17/12-2 well stratigraphy (table 3.1), drilled on the Sele High, which contains the Rotliegend deposits. Another well 25/8-1 on the Utsira high also encountered a thin succession of the Rotliegend. This well was used for this study purpose, but it is not mentioned in table 3.1. The strata present in the hanging wall of rotated fault blocks are thickening towards the fault and is mostly truncating into the Base Zechstein. This shows the syn-rift deposition (fig. 4.3.b and 4.4). The Base Zechstein is lying straight on top of these syn-rift sediments, therefore marking a boundary between syn and post-rift stages.

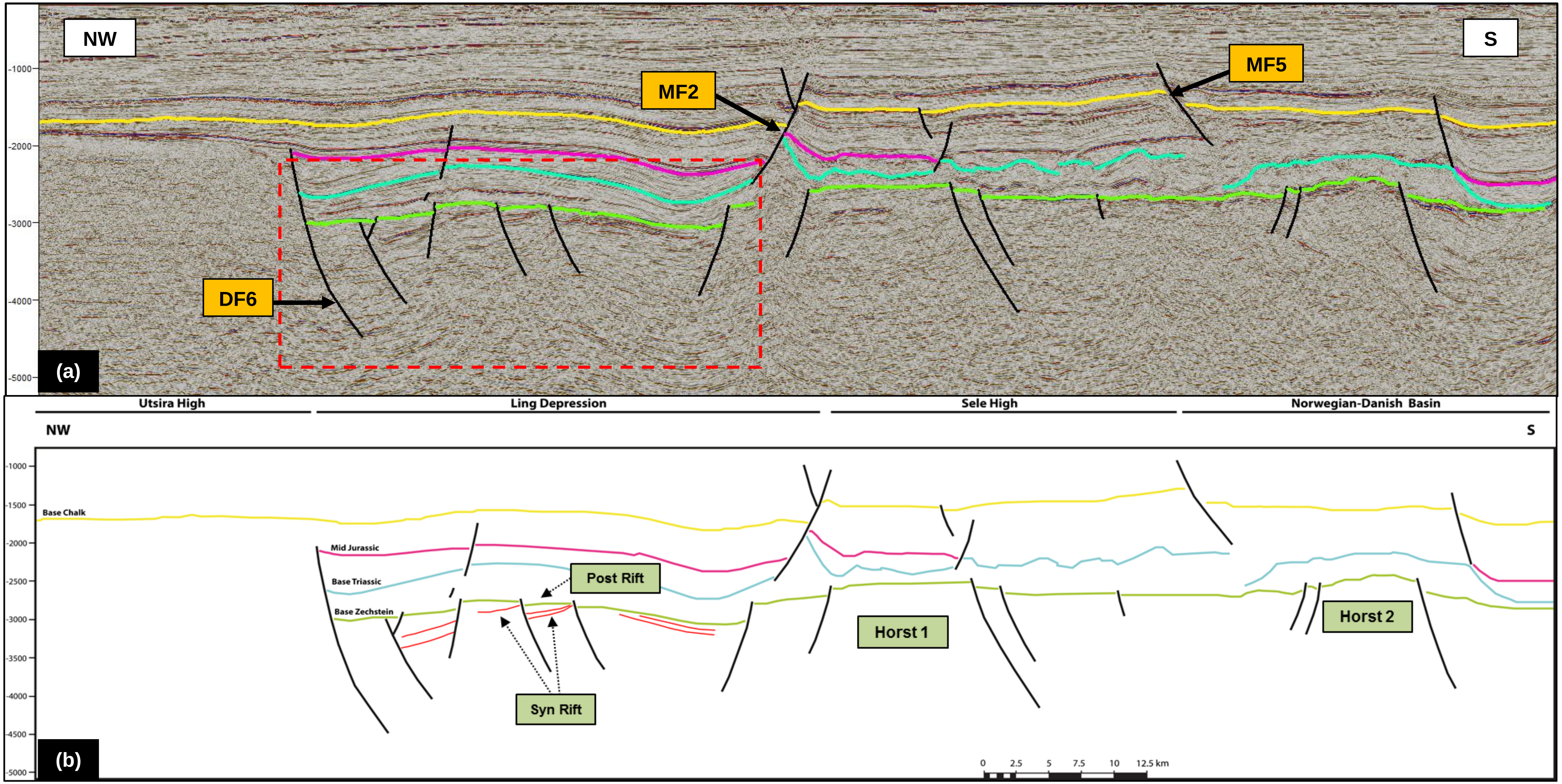


Figure 4.3: (a) Interpreted regional key Seismic Profile 1. The location of this key profile is shown in fig. 4.2. Red rectangle outlines the zoomed part of key profile 1 shown in fig. 4.4. **(b)** Interpreted line-drawing of key profile 1 with some structural features and name of main horizons (for details on horizons see table 3.2). Interpretation in red color is showing probably the Early to pre-Permian strata. (Note: Horizontal scale for **(a)** and **(b)** is same)

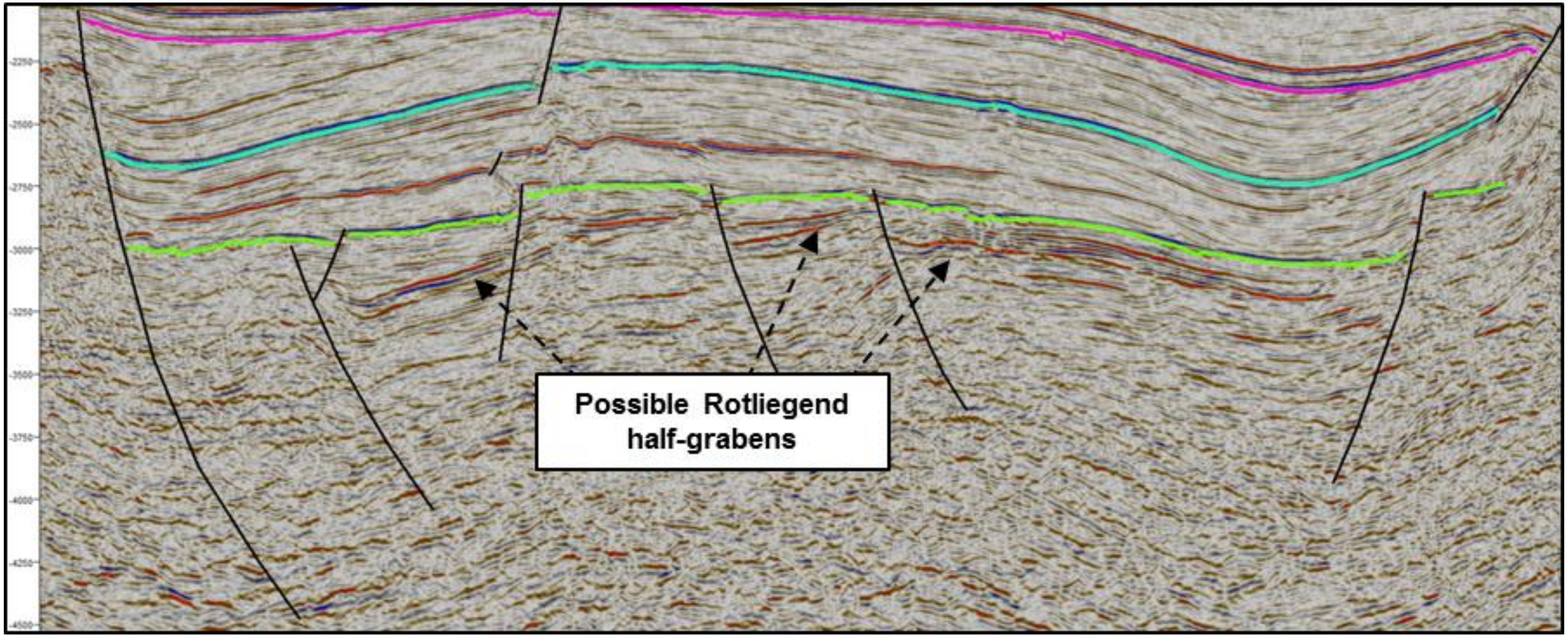


Figure 4.4: Close-up of regional key seismic profile 1, where the rotated half-grabens can be observed below the Base Zechstein horizon.

4.3.2. Key seismic profile 2

The key profile 2 has NW-SE strike (fig. 4.1). The lateral extent of this profile covers all the main structural elements of the study area. The NW side of the profile covers the Utsira High. Then it runs across the lateral extent of the Ling Depression and into the Sele High. It is covering almost all the lateral extent of the Sele High from the NW-SE. It ends into the Egersund Basin which lies towards the SE of the Sele High (fig. 4.5.a). This line cross cuts three main faults covered in the study area which are DF6, MF2 and MF6 (fig. 4.2).

DF6 is separating the Utsira High from the Ling Depression (fig. 4.5.a) and is a bounding fault in the study area. On Key Profile 2 this fault is cutting the Base Triassic and the Base Zechstein horizons. The throw of this fault is upto 4500 ms TWT on seismic section. Within the Ling Depression, an antithetic secondary fault with respect to DF6 is cutting deeper three key horizons. Towards its SE on the seismic profile, another secondary fault is running below the Late Permian stratigraphic level (fig. 4.5.b). It is forming a rotated half-graben structure possibly of Early Permian age (fig. 4.5.b and 4.6). Further towards the SE in the Ling Depression area, another large-scale fault is observed which is cutting the upper three key horizons. It is forming a conjugate fault pattern with respect to MF2 (fig. 4.5.a). MF2 is separating the Ling Depression from the Sele High and has opposite dip direction related to DF6. On the NW part of the Sele High, two normal faults with opposite dip direction are forming a horst feature (Horst 3) at the mid-Jurassic level (fig. 4.5.b). Further down along the seismic profile in the Sele High, few faults are present at the Base Chalk stratigraphic level, which are synthetic to MF2. Another horst structure (Horst 4) is observed at the mid-Jurassic level on the SE part of the Sele High (fig. 4.5.b). It is bounded by two faults out of which one fault is the main fault (MF6). MF6 is separating the Sele High from the Egersund Basin in the SE. There is a large-scale antithetic fault with respect to MF6 in the Egersund Basin (fig. 4.5.a).

Interpretation of the four main horizons (table 3.2) is better constrained on this key profile because there are three wells present on this seismic line. There is a presence of one well each, on all the three main structural elements related to the study area (Utsira High, Ling Depression and Sele High). Two shallow horizons (Base Chalk and mid-Jurassic) are interpreted on the Utsira High. The Base Chalk is present throughout the Utsira High but the Mid-Jurassic horizon is interpreted on just the SE flank of the high, as it pinches into the overlying strata. Moving towards the SE along the profile, we have the Ling Depression. All the four main horizons are interpreted in the Ling Depression using well tops from well 17/4-1 (see table 3.1). The lateral extent of all the horizons is present throughout the Ling Depression but the thickness of the salt varies (fig. 4.5.b). The salt layer is thin in between the set of two faults forming the conjugate fault pattern. However further towards NW in the Ling Depression there is a thick halite sequence and this is probably not distorted due to halokinesis (fig. 4.5). Well 17/4-1 is drilled directly through this thick halite sequence. On the NW part of the Sele High the salt succession is absent on a horst type structure (Horst 3). In the central part of the Sele High all four horizons are interpreted, except with some termination of the mid-Jurassic Horizon into the Base Triassic horizon (fig.4.5). There is lots of disturbance in the salt sequence probably due to halokinesis. On the SE edge of the Sele High, we again have a presence of the horst structure (Horst 4). The well is drilled on the edge of this horst 4 in the Sele High. The salt succession is also absent on this part of the Sele High (see well 17/12-2 in table 3.1) but a thin sequence of Rotliegend (Early Permian) strata is encountered in this well. It is clearly observable on the key profile 2 that the Sele High is bounded by two horst type structures where salt is absent (fig. 4.5.b). After the Sele High, we enter into the Egersund Basin along seismic profile towards the SE. Only the Base Chalk horizon is interpreted in this part of seismic section. Slumping of sediments is observed within the V-shape structure formed by MF6 and its antithetic fault in the Egersund Basin area (fig. 4.5.a). So it was very difficult to interpret other three horizons as there is no continuity of these reflectors.

The Rotliegend is encountered in two wells (17/4-1 and 17/12-2) present on this key profile (table 3.1). The interpretation of strata below the Base Zechstein is very difficult, as the seismic quality is not good at greater depths. There is no continuity of any reflection below 3000 ms TWT. Some minor interpretations below the Base Zechstein are done within the Ling Depression (fig. 4.6). Possibly the Rotliegendes are truncating in the Base Zechstein which is almost lying straight on top of it. One rotated fault block is interpreted below the thick halite sequence (fig. 4.6). The strata are getting thick towards the DF6 and thinning away. Finally it terminates into the Base Zechstein (fig. 4.6). This possibly shows a syn-rift stage during the Early Permian period, when faulting was probably active.

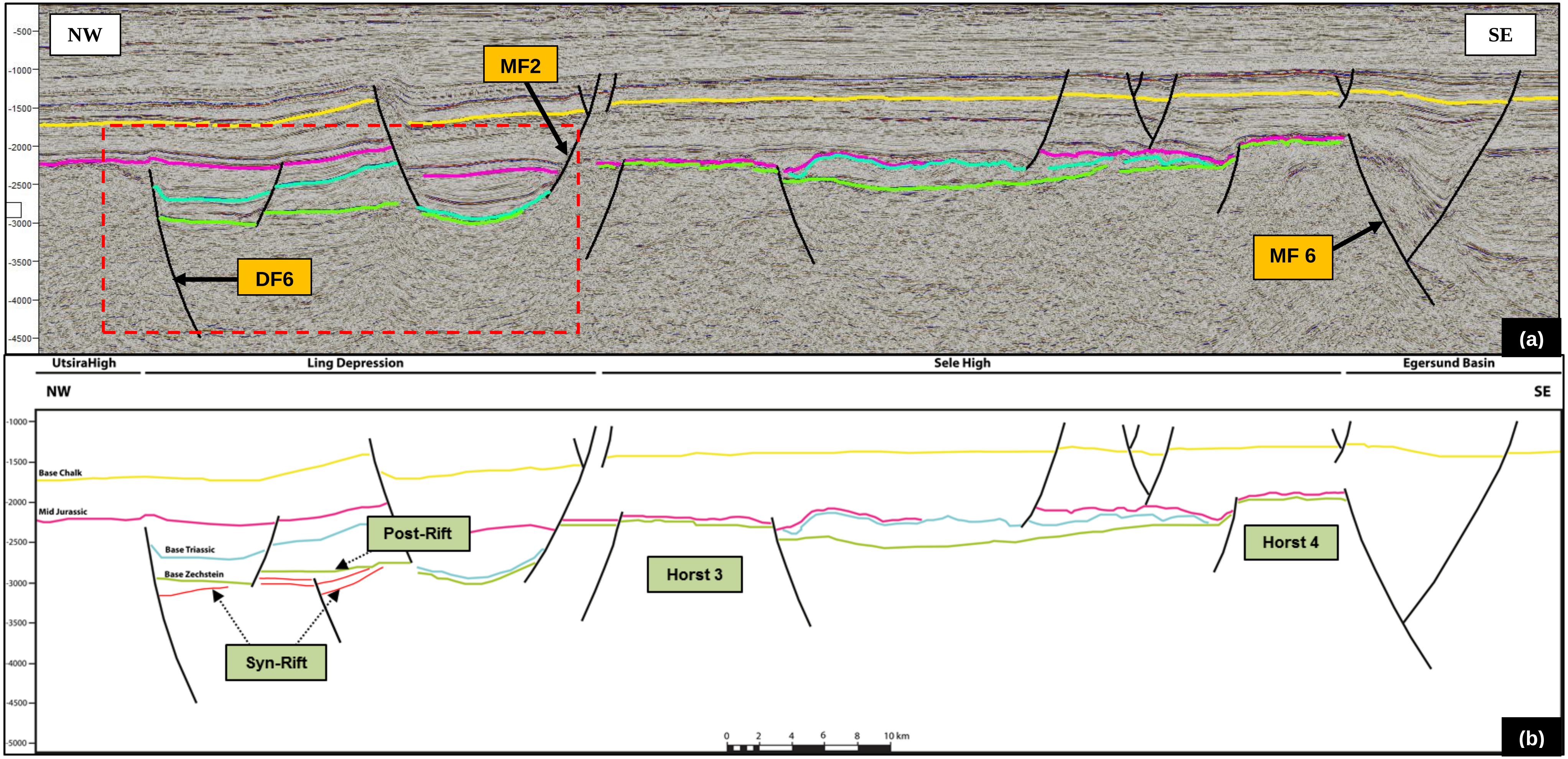


Figure 4.5: (a) Interpreted regional key seismic profile 2. The location of this key profile is shown in fig. 4.2. Red rectangle outlines the zoomed part of key profile 2 shown in fig. 4.6. **(b)** Interpreted line drawing of key profile 2 with some main structural features and name of main horizons (for details on horizons see table 3.2). Interpretation in red color is showing probably the Early to pre-Permian strata. (Note: Horizontal scale for **(a)** and **(b)** is same)

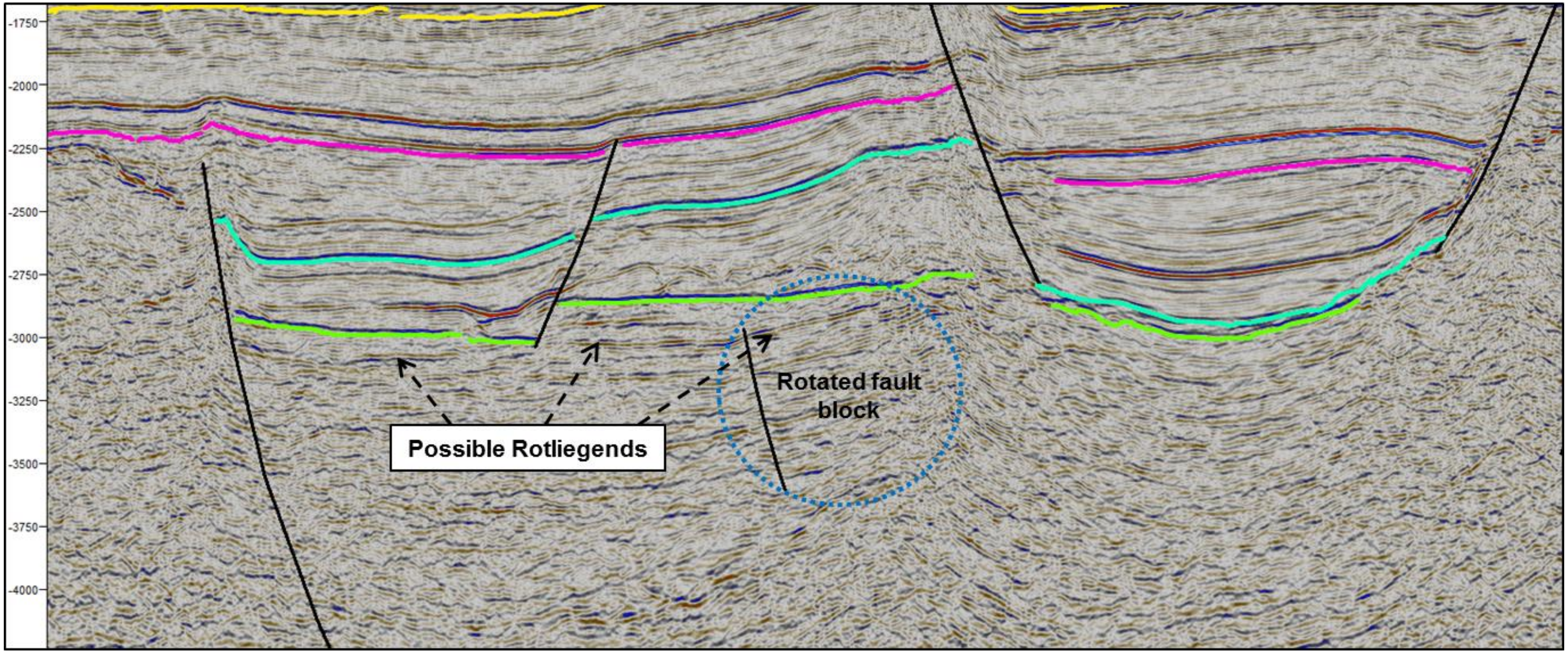


Figure 4.6: Close-up of regional key seismic profile 2, where we can see the possible Rotliegendes and rotated fault block.

4.3.3. Key seismic profile 3

The strike of this key profile 3 is WSW-ENE (fig. 4.1). In the WSW direction this profile covers the southern tip of the Utsira High. Mostly this profile runs within the lateral extent of the Ling Depression and finally into the Åsta Graben towards the ENE**.** Thus, this key profile lies parallel to the lateral trend of the Ling Depression (fig. 4.7.a). This seismic line do not covers the Sele High. It crosscut only one main fault, MF3, covered in the study area. The main purpose of this key profile is to look for the structures in the Ling Depression along its lateral extent.

MF3 is separating the Utsira High from the Ling Depression (fig. 4.2). There are several secondary faults observed within the Ling Depression area covered by this seismic profile. Most of the faults are at the Base Zechstein or the Early Permian stratigraphic levels. These faults are forming half-grabens within the Ling Depression. As seen in figure 4.7, a low angle fault at the Early Permian level is dipping in the ENE direction within the Ling Depression and is synthetic to MF3. Another antithetic fault, with respect to MF3, cutting at the Base Zechstein stratigraphic level is opposite in dip direction to that fault. They are forming horst-graben structures within the Ling Depression towards the ENE of this seismic profile (fig. 4.7.b). Towards the ENE side of the horst structure (Horst 5), faults at the Base Zechstein stratigraphic level are forming a step like geometry. The normal faults are also observed at the Base Chalk and the mid-Jurassic stratigraphic interval on this key profile within the Ling Depression. A small horst structure is also observed in the Åsta graben area. These opposing faults which are forming this small horst in the Åsta Graben are running deep into probably the Lower Paleozoic sedimentary rocks (fig. 4.7.a).

Only one well, 16/8-1, is present on this profile (see table. 3.1 for well stratigraphy). Therefore, mostly the interpretation of key horizons was carried out by seismic correlation on this key profile. Two key horizons (Base Chalk and Base Triassic) were interpreted from the well tops of the borehole present on this key profile. Towards the WSW part of the profile only two horizons (Base Chalk and Base Zechstein) are interpreted (fig. 4.7.b). All four main horizons are mostly interpreted within the Ling Depression area covered by this key profile (fig. 4.7.b). The thickness between the Base Chalk and the mid-Jurassic is less (approx. 300 ms TWT) towards the WSW direction but it increase many folds (approx. 1200 ms TWT) towards the ENE of the Profile (fig. 4.7.b). Further ENE the Base Chalk horizon truncates into the younger strata. However we have the lateral continuity of the mid-Jurassic horizon almost throughout this regional profile (fig. 4.7.b). The disturbance in salt is also observed in some parts of the profile which is certainly due to halokinesis. But mostly the salt top (Base Triassic Horizon) is undisturbed (fig. 4.7.b). Furthermore towards the ENE direction, in the Åsta Graben area, the Base Triassic and the Base Zechstein were not interpreted because of intense faulting at that stratigraphic intervals and no clear continuity of these horizons (fig. 4.7.a).

Due to the limitation in seismic data quality and no well penetration at deeper level below the Base Zechstein, it was challenging to do detailed interpretation of the Early to pre-Permian stratigraphy. Some small-scale interpretation of the Early to pre- Permian strata is done within the Ling Depression (fig 4.8). A half-graben structure is observed with the possible Rotliegendes of Early Permian. This half-graben has resulted along a low angle listric fault which caused the rotation of fault block below the Upper Permian. The strata within this rotated fault block is truncating into the Late Permian Base Zechstein, which is almost lying straight on top of it (fig. 4.8). This is probably marking the boundary between the syn-rift and post-rift stages but the opposing fault towards the eastern side of the profile (fig. 4.8) within the Ling Depression, is cutting through the Base Zechstein, which possibly shows that faulting activity was going-on in the Late Permian time. One of the most prominent structure observed in the Base Cretaceous level, is the anticline. This may represent an element of inversion in the Early-Late Cretaceous times (fig. 4.9).

4.3.4. Key seismic profile 4

The strike of this key profile is from the WNW-ESE (fig. 4.1). It crosscut the two main faults MF2 and MF6 (fig. 4.2). The WNW side of the profile covers the southern margin of the Ling Depression. Then further towards the east it cuts main fault MF2 and enters into the Sele High area (fig. 4.10.a, see also fig. 4.2). MF2 separates the Ling Depression from the Sele High in the study area. This seismic profile covers the northern part of the Sele High. Furthermore towards the ESE, it crosscuts another main fault MF6 (fig. 4.10.a, see also fig. 4.2) which separates the Sele High from the Åsta Graben. This key profile covers a small western part of the Åsta Graben.

Two major deep faults are observed with dip direction towards the ESE on the Sele High (fig. 4.10.a). These two faults in the Sele High region are bounding a large tilted fault block (fig. 4.10 and 4.11). Further towards eastern side of the Sele High, normal faults are forming step like geometry. These faults are all synthetic with respect to MF6 (fig. 4.10.a). Only few faults are observed at the Base Chalk stratigraphic level of this profile and there are no faults observed at the mid-Jurassic and the Base Triassic stratigraphic levels throughout the profile (fig. 4.10.b). No faults are observed in the Åsta Graben area covered by this profile.

There are no boreholes present on this key profile, so the interpretation of key horizons was completed on the basis of seismic to seismic correlation on this profile. We find all the four main horizons (see table 3.2) in the Ling Depression area covered by this seismic line (fig. 4.10.b). This line shows severe salt activity. We can clearly observe a major salt diapir in the Ling Depression which crosscuts the two main shallow horizons (mid-Jurassic and Base Chalk) related to the study (fig. 4.10.b). There was some difficulty in marking the reflectors on the NW side of the Sele High due the presence of another salt diapir (fig. 4.10.b). The presence of salt in this area has obscured the seismic image. Therefore, all the horizons were picked by seismic correlation. Further towards the SE flank of the Sele High, the salt is absent along the seismic profile. The salt layer gets thinner towards this side of the Sele High and pinches into the Base Zechstein horizon (fig. 4.10.b). On the other hand, thickness between the Base Chalk and the Base Triassic horizon increases towards the ENE side of the seismic profile. In the Ling Depression thickness is less (approx. 500 ms TWT) and in the northeastern part of the Sele High thickness between these two horizons is approx. 800 ms TWT on the seismic (fig. 4.10.a). Towards the ENE direction, this profile covers only small portion of the western side of the Åsta Graben. But due to bad seismic quality in deeper parts, the two deeper horizons (Base Triassic and Base Zechstein) are not mapped (fig. 4.10.a). The Base Chalk reflector dies out further into the Åsta Graben. This may be probably due to truncating of Base Chalk into younger strata. Only the mid-Jurassic horizon is picked clearly in the Åsta Graben area along this key profile (fig. 4.10.b).

The seismic image quality is obscured in deeper parts of the Ling Depression. There are lots of distortions in seismic due to a large salt diapir. But some strong reflections are observed in minor part of a rotated half-graben containing possibly the Rotliegend in deeper parts of the Ling Depression (fig. 4.10.b). One reflector in this rotated half-graben, possibly representing the Top Rotliegend containing clastics, is lying straight beneath the Base Zechstein but deeper into this half-graben there are strong reflections dipping down towards the fault (fig. 4.10.b). They are thickening towards the hanging wall and pinching on the Base Zechstein, which probably shows it as a syn-rift event of the Early to pre-Permian time (fig. 4.10.b). And probably the continuation of this tectonic event is upto the Late Permian as the fault is cutting through the Base Zechstein (fig. 4.10.b). Other very prominent and large-scale deep structure is observed on the NE side of the Sele High. A clear tilted large-scale fault block is observed with some clear reflections in the deeper part (fig. 4.11). All the reflections are truncated into the Base Zechstein or the potentially Early Permian strata belonging to the Rotliegendes (fig. 4.11). These truncated reflections may be of the Early Paleozoic age (possibly Devonian or Carboniferous) and are possibly pointing towards an earlier tectonic event. But due to the lack of well data in the deeper levels upto to the Lower Paleozoic, no sharp and authentic statement can be given for these reflections.

4.3.5. Key seismic profile 5

The strike of this key profile is from the NW-SE and is located in the southwestern part of the study area (fig. 4.1). Along its extent from the NW side, it covers two main structural elements which are the Utsira High and the Ling Depression. The SE side of this profile is covering some part of the Norwegian-Danish Basin (fig. 4.12.b). This seismic section crosscuts the two main faults which are MF3 and MF11 (fig. 4.2). MF3 is separating the Utsira High from the Ling Depression. Most of the secondary faults in the Ling Depression are antithetic with respect to MF3 (fig. 4.12.a). MF11 is separating the Ling Depression from the Norwegian-Danish Basin in SE of the study area. MF11 is synthetic with respect to MF3 (fig. 4.12.a).

There is no borehole present on this regional key profile. The interpretation of the key horizons was completed on the basis of seismic correlation along this profile. In the NW side of the seismic section only one main horizon (Base Chalk) is interpreted on the Utsira High (fig. 4.12.b). The interpretation of the other three main horizons was not possible to carryout in this part of the key profile. Further down towards the south on the seismic section, all four main horizons are interpreted in the Ling Depression (fig. 4.12.b). The area of the Ling Depression is faulted to great extent on this profile but the ties from other seismic were quite helpful in interpreting these horizons. The Base Zechstein is present in almost all the area of the Ling Depression except on the horst structure (Horst 7) which is present in between the Ling Depression area on this profile (fig. 4.12.b). The Base Triassic is interpreted throughout the extent of the Ling Depression on this profile. The salt top is disturbed at some places in the Ling Depression but a major salt diapir is observed on the SE side of the seismic section within the Ling Depression (fig. 4.12.b). This diapir has penetrated up to the Base Chalk horizon and has faulted the upper region which has distorted the seismic image. At the end of seismic section on the SE direction, lies the Norwegian-Danish Basin which is separated from the Ling Depression by MF11 (fig. 4.12.a). All the four horizons are present in the basin area. The salt sequence is very thin in this part because the salt extruded to form the diapir on its northwestern side within the Ling Depression (fig. 4.12.b).

There are some features interpreted below the Base Zechstein. On the NW side of the profile in the Ling Depression, there is a rotated fault block forming the half-graben structure (fig. 4.13). Some clear reflections are observed within this rotated half-graben which may be the potential Rotliegendes (fig. 4.13). These deep reflections are terminated into the Base Zechstein horizon, which possibly represents as the local unconformity in this area. Another half-graben is observed on the SE side of the initial rotated half-graben (fig. 4.13). Reflector marked in this half-graben structure below the Base Zechstein, is lying almost straight below it (fig. 4.12.b and 4.13). This can be possibly the base of Rotliegend clastics. More towards the SE side of the Ling Depression there is large horst structure (Horst 7) which is bounded by two deep faults with maximum throw upto approximately 4000 ms TWT, towards its southeastern side (fig. 4.12). Two deep reflections on the southeastern side of the Horst 7 probably are representing the Lower Paleozoic stratigraphy present within the Ling Depression (fig. 4.12.b), but there is no mature data or evidence to give strong statement regarding the Early Paleozoic sediments in the Ling Depression.

4.3.6. Key seismic profile 6

The strike of this regional seismic profile is the NW-SE (fig. 4.1). It is mostly covering the parts of the Ling Depression and small part of the Norwegian-Danish Basin. It only covers the NW tip of the Sele High. The seismic section is cross cutting the Ling Depression from its SW lateral extent. More towards the SE side of the section; it is cutting the NW tip of the Sele High and again enters into the Ling Depression. This key profile finally terminates into small northern part of the Norwegian-Danish Basin (fig. 4.14.b). This regional profile is covering the two main faults, MF2 and MF11, and several other secondary faults (fig. 4.2).

MF2 is the main fault separating the Ling Depression and the Sele High (fig. 4.2), whose throw is upto the Base Triassic (2650 ms TWT) (fig. 4.14.a). But as mentioned above, the seismic section is just cutting the NW tip of the Sele High, and a salt diapir has penetrated upto the Base Chalk level due to which no features are interpreted in this part of the Sele High on this profile. To the SE of MF2 there is a synthetic fault which is branching away from it (fig. 4.14.a). There is one antithetic fault whose throw is down to the mid-Jurassic horizon (fig. 4.14.a). Deep faults interpreted below the Base Zechstein stratigraphic level are mostly synthetic with respect to MF2 (fig. 4.14.a). Faults cutting the mid-Jurassic stratigraphic level are mostly antithetic with respect to MF2 (fig 4.14.a). In the NW side of seismic profile, from the Upper Cretaceous upto the Base Triassic stratigraphic level, there are two secondary faults in the Ling Depression area which have opposite dip direction and are forming a horst type structure (Horst 8) (fig. 4.14.b). Just below the salt in the same part of seismic section, there is large horst structure (Horst 7) within the Ling Depression (fig. 4.14.b), formed by two opposing deep faults with maximum throw upto approximately 5000 ms TWT (fig. 4.14.a). MF11 is separating the Ling Depression and the Norwegian-Danish Basin (fig. 4.2) towards the SE of the key profile (fig. 4.14.a). Its throw is also upto the Base Triassic (approx. 2700 ms TWT).

There were no wells present on this seismic section. So interpretation is carried out on the basis of seismic correlation. The four main horizons are interpreted almost throughout on this key profile (see table 3.2). On the NW side of the profile in the Ling Depression, the Base Zechstein is absent on the horst 7 (fig. 4.14.b). And more towards the SE side of the profile the Base Zechstein is not interpreted due to poor seismic quality below the salt in the Ling Depression. The Base Zechstein reflector is very prominent towards the end of profile in the Norwegian-Danish Basin. The Base Triassic horizon is interpreted throughout the lateral extent of the profile except in the Norwegian-Danish Basin, where it is terminated into the Base Zechstein. The Base Triassic is mostly disturbed on this regional profile due to upward movement of the salt. There is salt movement observed on top of the Horst 7 in the NW part of the profile (fig. 4.14.b). Further down towards the SE of the section, in the Ling Depression, the Base Triassic is totally disturbed due to presence of two large salt diapirs (fig. 4.14.b). The mid-Jurassic horizon is only missing in the SE part of profile, above the two salt diapirs. Otherwise it is easily interpreted throughout the seismic section with a prominent reflection present at this level. As usual, the Base Chalk is present throughout this seismic profile (fig. 4.14.b) and easily interpreted on the basis of seismic to seismic correlation. If we move along the NW side to the SE side of a profile, the thickness between the Base Chalk and the mid-Jurassic horizons increases. Towards the NW a thickness is approximately 350 ms TWT and increases upto 700 ms TWT towards the SE on the seismic section (fig. 4.14).

The same horst structure (Horst 7) is also observed in this profile, as it was observed in the key profile 5 (fig. 4.12.b). The two opposing deep normal faults are forming this horst structure below the Early Triassic (fig. 4.15). The clear reflectors are on-lapping on these two opposing normal faults (fig. 4.15). The reflection seen just below the Base Zechstein horizon may possibly represent the Rotliegendes and the reflections observed towards the SE of horst structure (Horst 7), deep below the Base Zechstein, may possibly be Lower Paleozoic strata (fig. 4.15). These deep reflections are showing tilted stratigraphy. The relatively small horst structure (Horst 8) seen on top of horst 7 (fig. 4.14.b), may have formed possibly by the continuity of these deep faults. But they are impossible to trace upto that stratigraphic level due to presence of the ductile and mobile salt layer between them. A strong reflector is also seen into the Norwegian-Danish Basin towards the SE of the profile. This may represent potential Rotliegend deposits in that part of the basin (fig. 4.14.b).

4.3.7. Key seismic profile 7

The strike of this seismic key profile is from the NW-SE (fig. 4.1). It almost lies in the central part of the study area in such a way that it cuts two main structural elements along its strike (fig. 4.2). From the NW side, this seismic section perpendicularly crosscuts the central part of the Ling Depression and enters into the Sele High and follows the lateral extent of this high towards the SE (fig. 4.16.b). It only covers the northern and the central parts of the Sele High with respect to its trend (fig. 4.2).

This seismic section only crosscuts one major fault which is MF2 (fig. 4.2). This fault separates the Ling Depression from the Sele High (fig. 4.16.a, see also fig. 4.2). Most of the secondary faults on this profile are synthetic with respect to MF2 (fig. 4.16.a). On the SW side of the section in the Ling Depression, there is a normal fault which is synthetic to MF2. It is cutting three key horizons of the study area (mid-Jurassic, Base Triassic and Base Zechstein) (fig. 4.16.a). Its throw is approximately upto 3000 ms TWT on seismic section. Two small-scale faults are also observed adjacent to it. They also have the same NW dip direction and are cutting only the Base Triassic horizon related to study (fig. 4.16.a). Moving further into the Ling Depression relative to this profile, there is one antithetic fault present at the Base Triassic level. It forms a conjugate fault pattern with respect to MF2 (fig. 4.16.a) which is resulting in a depression like structure. On top of this fault there is probably a small-scale reverse fault which is branching out of it (fig. 4.16.a). This is probably representing an inversion structure at the Late Jurassic to Early Cretaceous stratigraphic level. Further towards the SE of the seismic section there are two faults dipping in opposite direction, hence forming a horst like structure (Horst 3) (fig. 4.16.b). The same horst structure is also observed on the key profile 2 (fig. 4.5.b). These faults are present at deeper levels with a maximum throw upto 3000 ms TWT on seismic section. At the edge of this key profile, there is one large fault present on the Sele High towards the SE. It is antithetic to MF2. This fault crosscuts three shallow key horizons of the study area (fig. 4.16.a).

There was only one well, 17/4-1, present on this seismic section towards the Ling Depression (see table 3.1 for well stratigraphy). All the four key horizons (see table 3.2) were present in this borehole. The interpretation of horizons was easy in the Ling Depression area on this profile. The Base Zechstein is mapped throughout on this seismic section (fig. 4.16.b). The Base Triassic horizon is interpreted on all the profile except on the NW side of the Sele High where seismic image is quite disturbed due to which it could not be interpreted at this certain area. Salt is absent on the horst structure (Horst 3) (fig. 4.16.b). There is a thick salt sequence observed in the Ling Depression area and it is undisturbed due to which the Base Triassic was easily interpreted here. But further away from horst geometry on the Sele High towards the SE, the Base Triassic horizon was disturbed to some extent which made it bit difficult to map it in this certain part (fig. 4.16.b). The mid-Jurassic horizon is present throughout the Ling Depression and was interpreted easily on this side without any difficulties (fig. 4.16.b). A strong reflection was picked on the mid-Jurassic level in the Ling Depression on this key profile. As we move from MF2 towards the SE of a profile, the seismic image is quite distorted at this specific location, probably due to intense minor faults, which made interpretation for the mid-Jurassic horizon difficult. The mid-Jurassic horizon is present on the horst (Horst 3). Furthermore towards the SE, away from the horst structure, there is disturbance of salt which made the interpretation bit difficult for this horizon. Some part of this horizon is interpreted towards the SE (fig. 4.16.b) by seismic-seismic correlation. The Base Chalk horizon was interpreted on all the key profile area (fig. 4.16.b). There was a strong positive reflection picked from the well top and further seismic correlation made it very easy to interpret this horizon on this section.

Mostly the reflections below the Base Zechstein level are difficult to interpret due to poor seismic data quality at depths. Only minor interpretation of probably the Early to pre-Permian strata is done in a small part of the Ling Depression (fig. 4.16.b). The well present on this section drilled a thin succession of the Rotliegendes, which makes it evident that upper reflection marked in figure 4.16.b, which is present directly below the Base Zechstein and is pinching into it, is potentially the Rotliegend reflector but absolute dating cannot be strongly determined due there detrital nature. The thickness of the Rotliegend cannot be determined as the well did not penetrate down to the base of it. Well data shows that it consists of very hard red conglomerates (npd.no). A strong reflection is also marked at a depth of approximately 3350 ms TWT on seismic (fig. 4.16.b and 4.17). Most probably this is the Lower Paleozoic strata buried at depth in the Ling Depression. Another most prominent and large-scale feature observed is the monoclinal structure in the Ling Depression (fig. 4.17). This is most probably representing an inversion at the Mesozoic level.

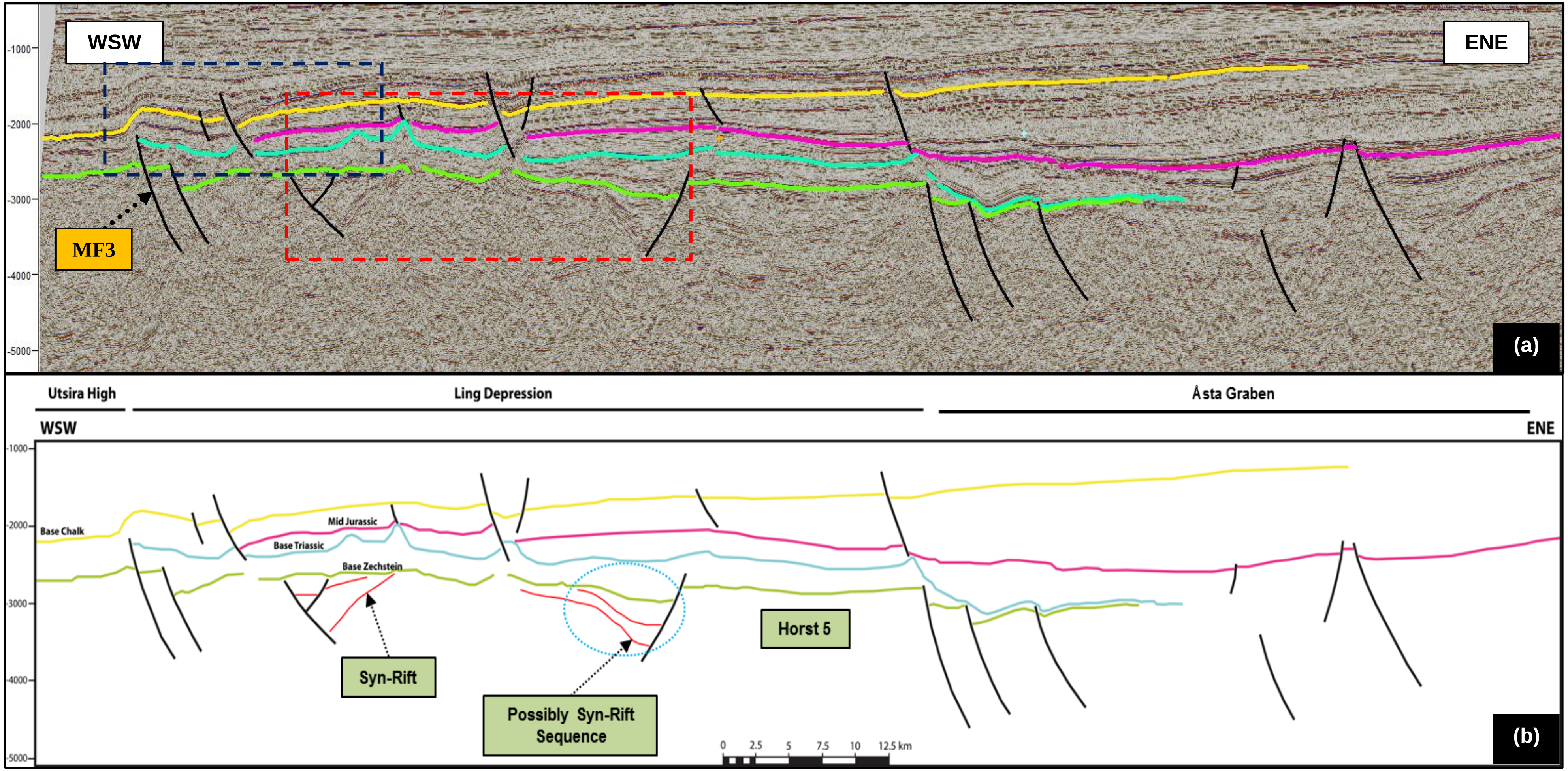


Figure 4.7: (a) Interpreted regional key seismic profile 3. The location of this key profile is shown in fig. 4.2. Red and blue rectangles outline the zoomed parts of key profile 3 shown in fig. 4.8 and 4.9 respectively. **(b)** Interpreted line drawing of key profile 3 with some main structural features and name of main horizons (for details on horizons see table 3.2). Interpretation in red color is showing probably the Early to pre-Permian stratigraphy. (Note: Horizontal scale for **(a)** and **(b)** is same)

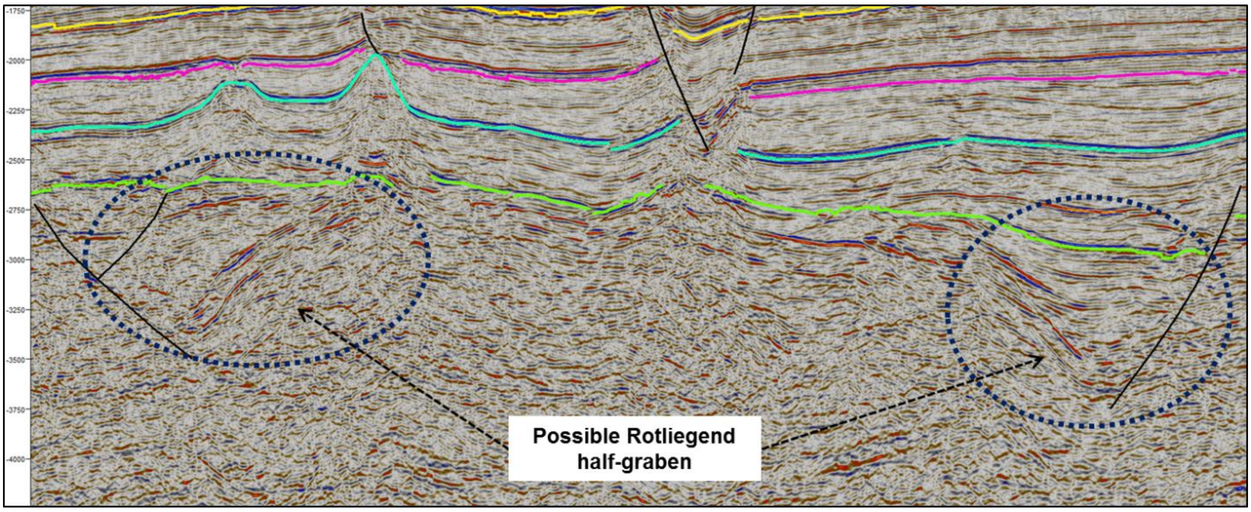


Figure 4.8: Close-up of regional key seismic profile 3, where we can see half-graben structures filled possibly with the Rotliegend succession.

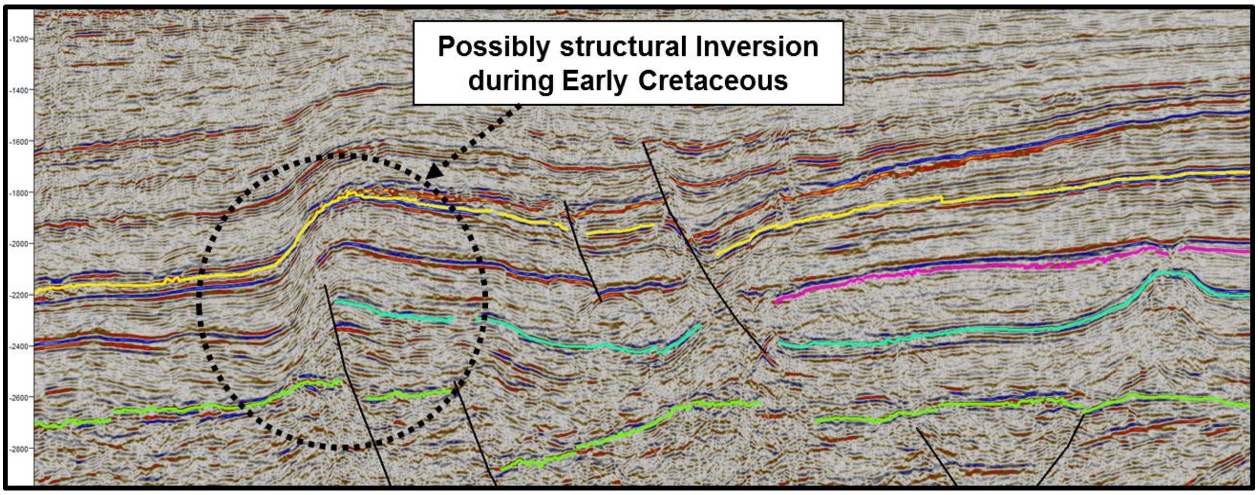


Figure 4.9: Close-up of regional key seismic profile 3, where we can see structural inversion.

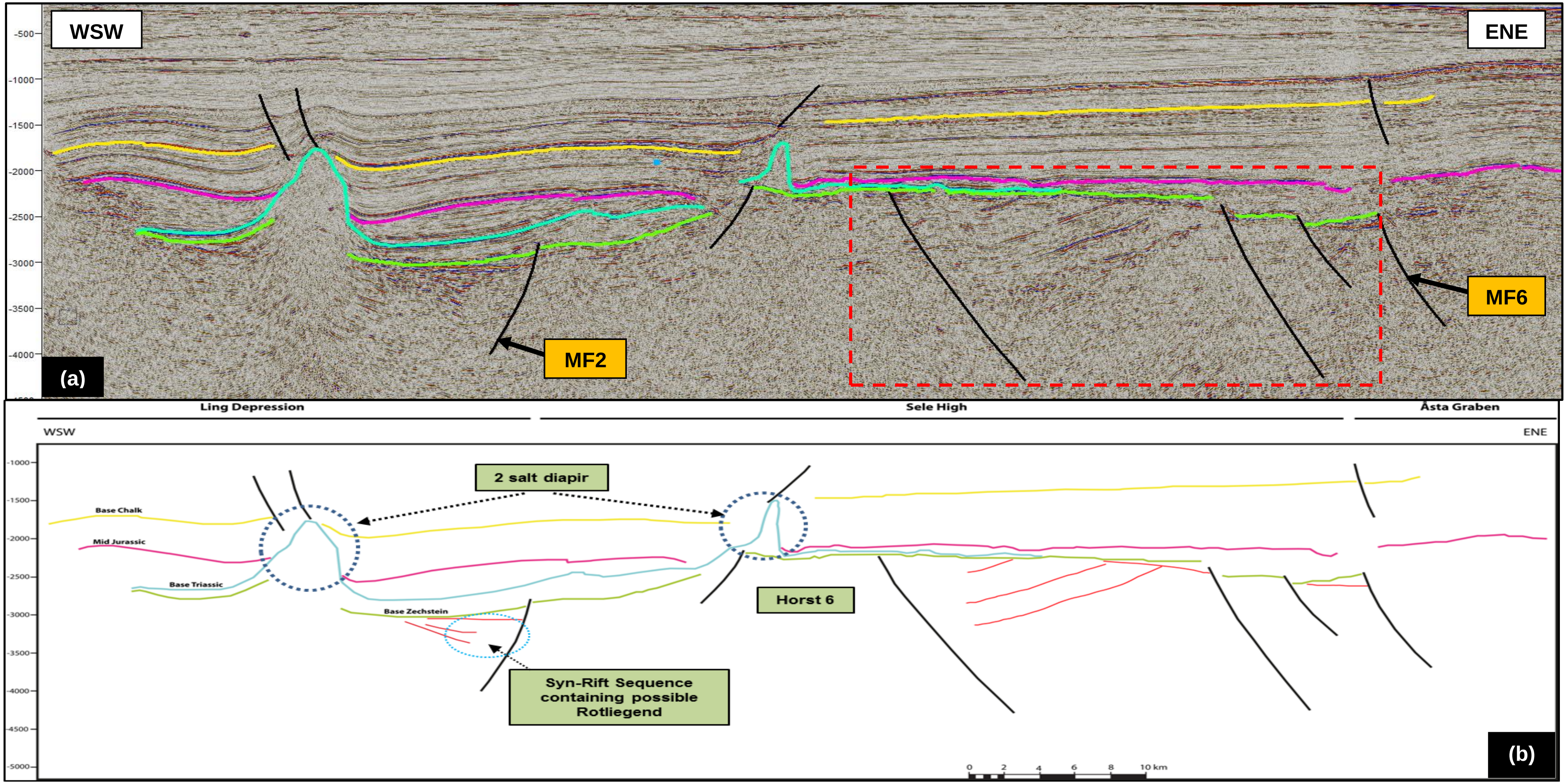


Figure 4.10: (a) Interpreted regional key seismic profile 4. The location of this key profile is shown in fig. 4.2. Red rectangle outlines the zoomed part of key profile 4 shown in fig. 4.11. **(b)** Interpreted line-Drawing of key profile 4 with some main structural features and name of main horizons (for details on horizons see table 3.2). Interpretation in red color is showing probably the Early to pre-Permian Stratigraphy. (Note: Horizontal scale for **(a)** and **(b)** is same)

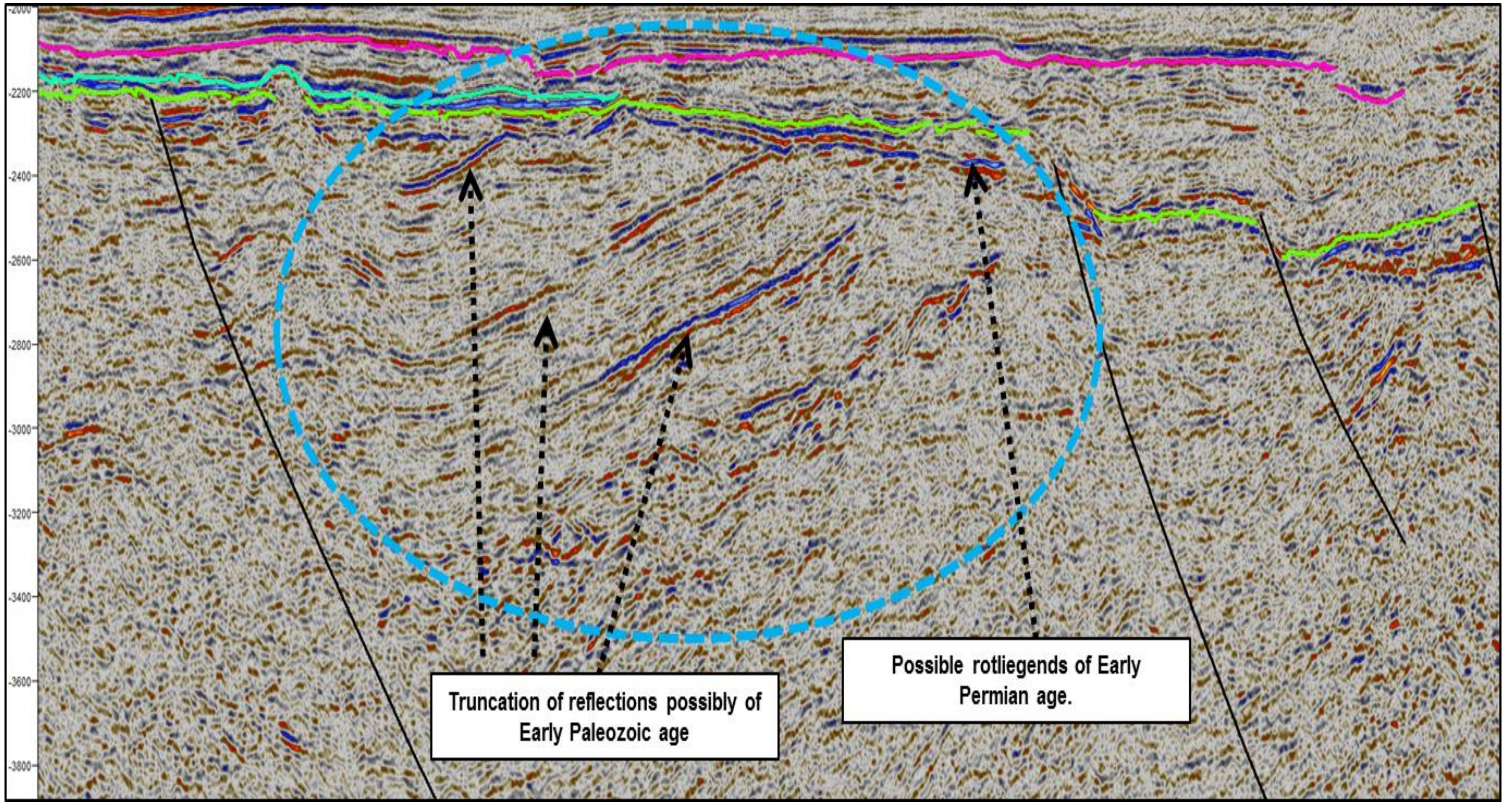


Figure 4.11: Close-up of regional key seismic profile 4, where clear truncation of probably the Early Paleozoic strata is observed in a large tilted fault block on the Sele High. It is most probably representing a compressional event.

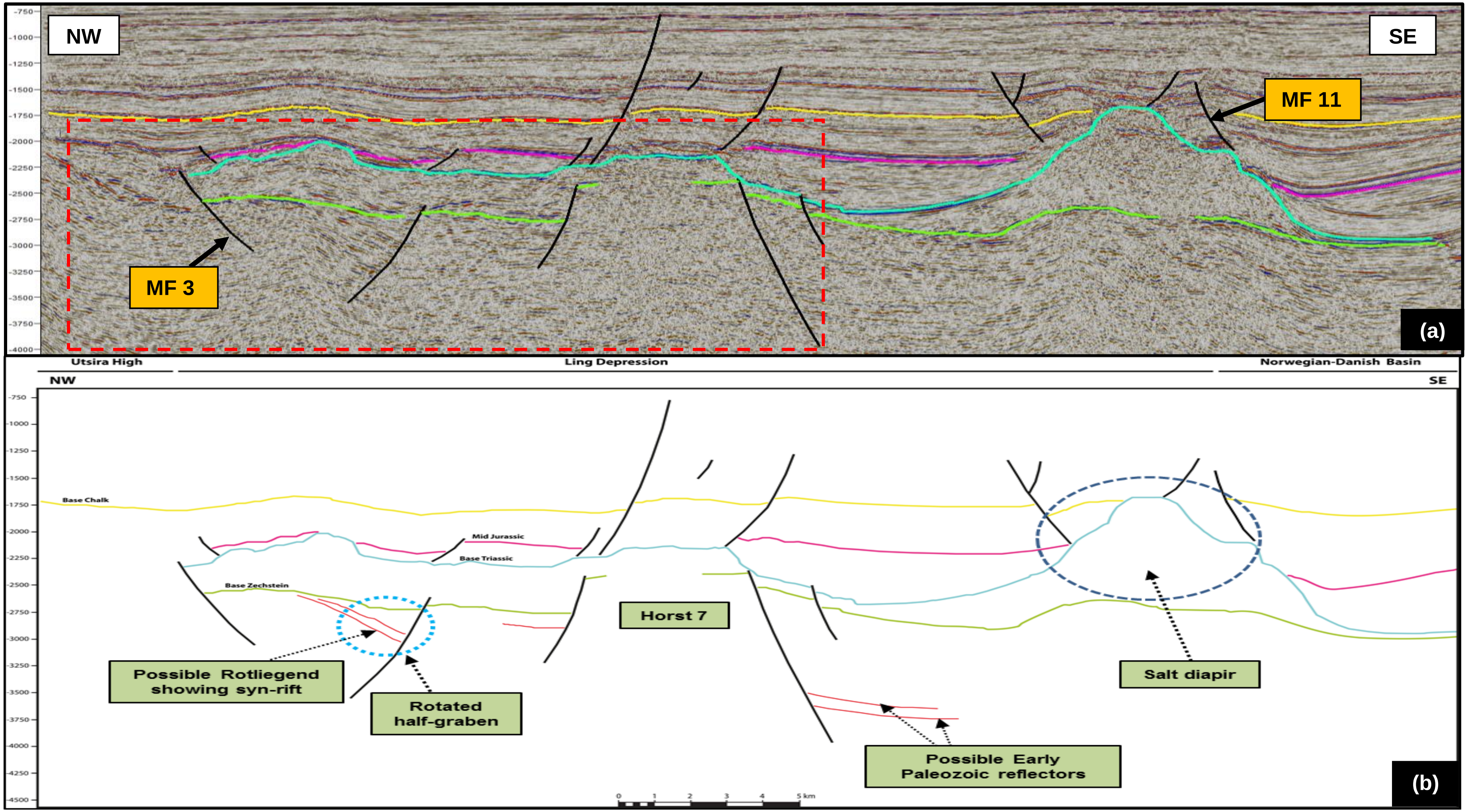


Figure 4.12: (a) Interpreted regional key seismic profile 5. The location of this key profile is shown in fig. 4.2. Red rectangle outlines the zoomed part of key profile 5 shown in fig. 4.13. **(b)** Interpreted line-drawing of key profile 5 with some main structural features and name of main horizons (for details on horizons see table 3.2). Interpretation in red color is showing probably the Early to pre-Permian stratigraphy. (Note: Horizontal scale for **(a)** and **(b)** is same)

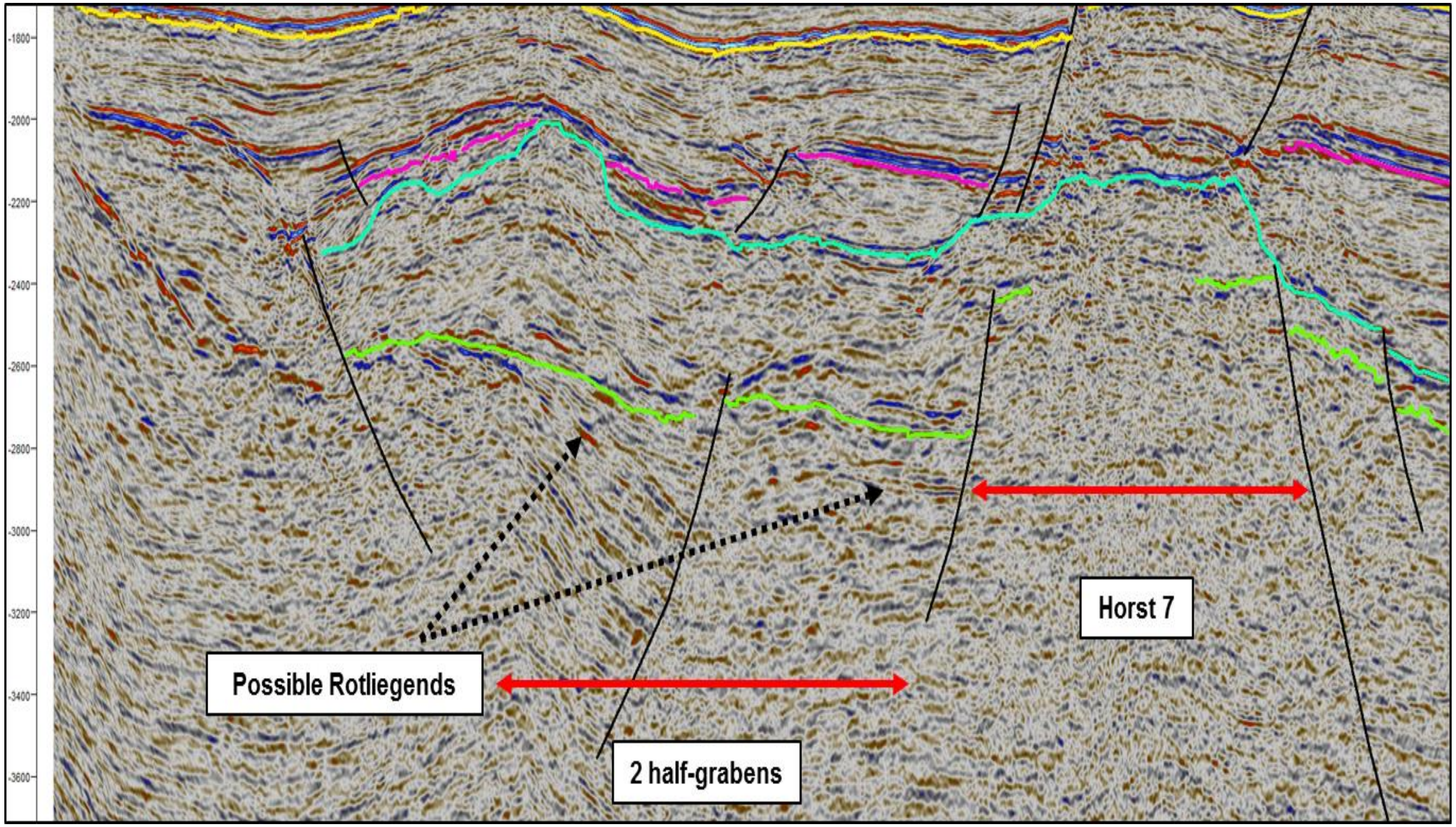


Figure 4.13: Close-up of regional key seismic profile 5, where horst-graben geometry is observed. The half-grabens are probably filled with the Rotliegendes.

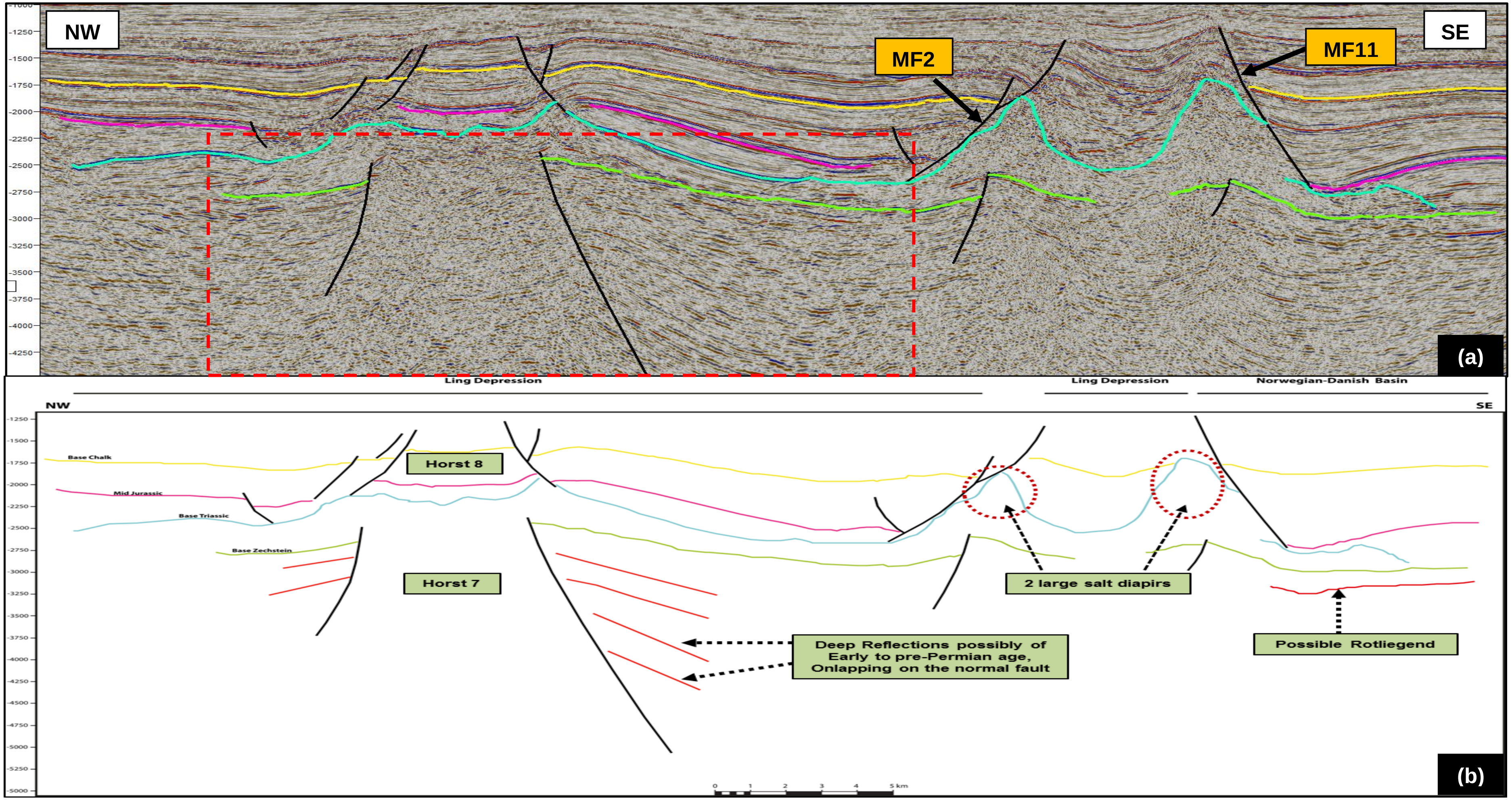


Figure 4.14: (a) Interpreted regional key seismic profile 6. The location of this key profile is shown in fig. 4.2. Red rectangle outlines the zoomed part of key profile 6 shown in fig. 4.15. **(b)** Interpreted line-drawing of key profile 6 with some main structural features and name of main horizons (for details on horizons see table 3.2). The interpretation in red color is showing probably the Early to pre-Permian stratigraphy. (Note: Horizontal scale for **(a)** and **(b)** is same)

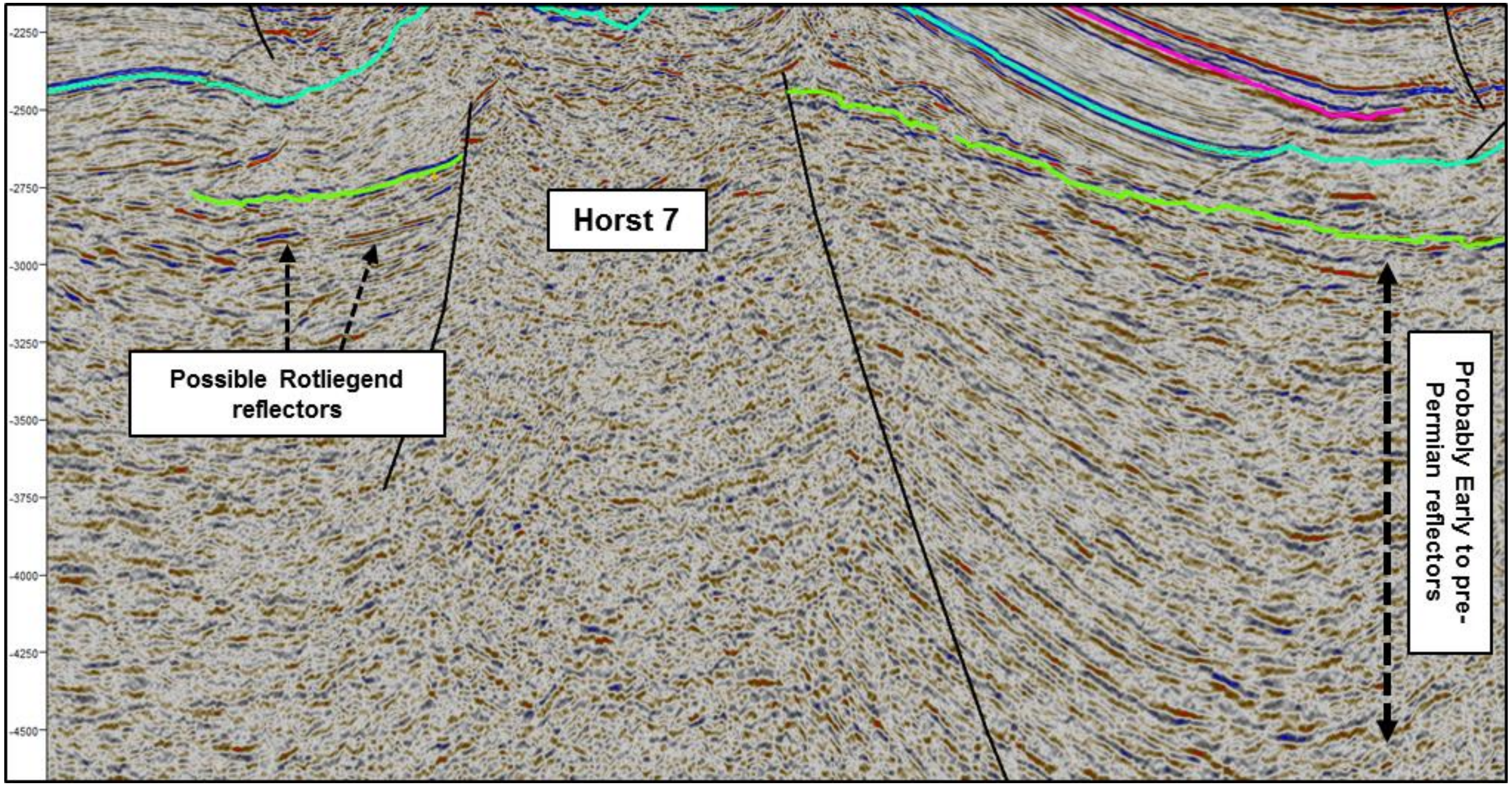


Figure 4.15: Close-up of regional key seismic profile 6, where large horst structure is observed, cutting probably the Early to pre-Permian stratigraphy.

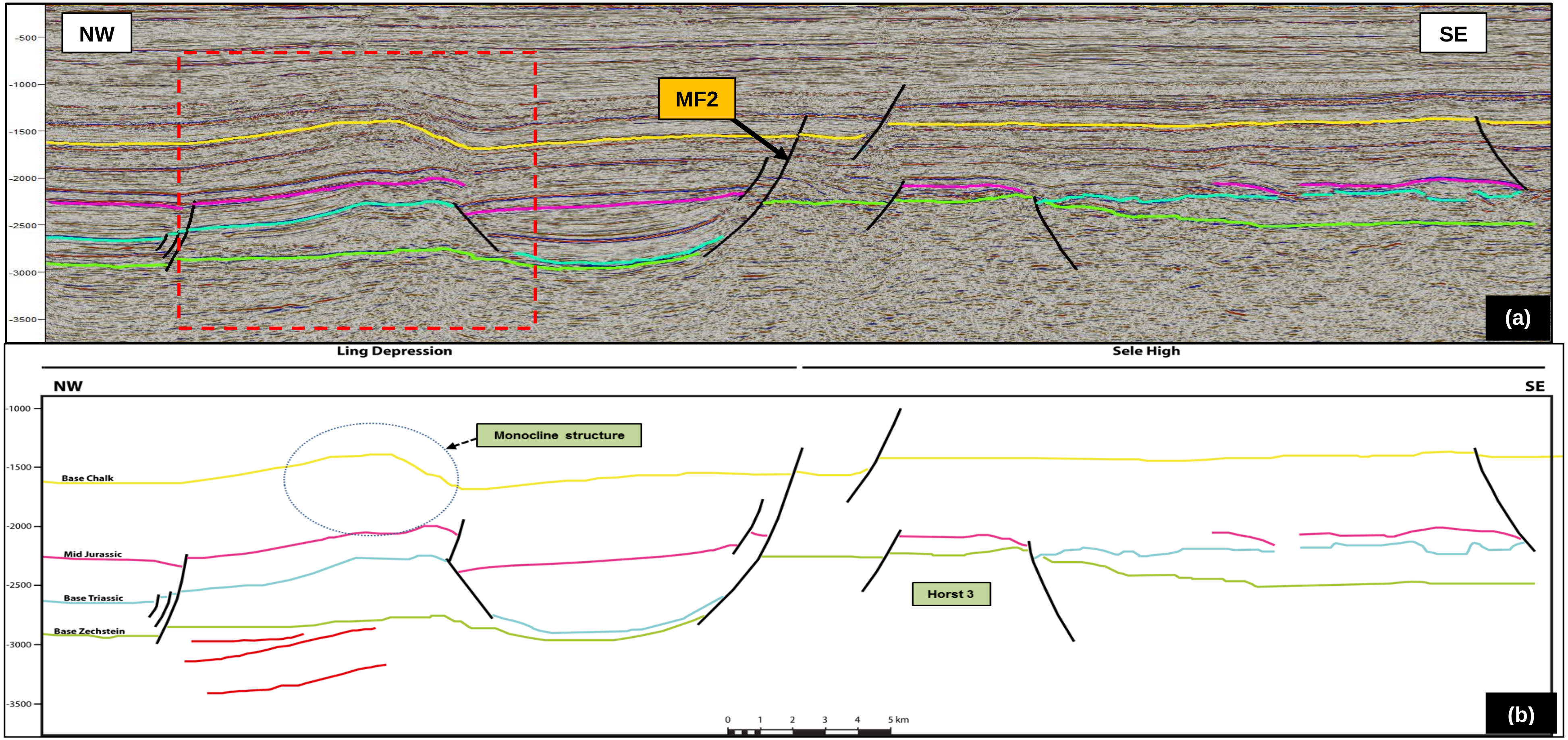


Figure 4.16: (a) Interpreted regional key seismic profile 7. The location of this key profile is shown in fig. 4.2. Red square outlines the zoomed part of key profile 7 shown in fig. 4.17. **(b)** Interpreted line-drawing of key profile 7 with some main structural features and name of main horizons (for details on horizons see table 3.2). Interpretation in red color is showing probably the Early to pre-Permian stratigraphy. (Note: Horizontal scale for **(a)** and **(b)** is same)

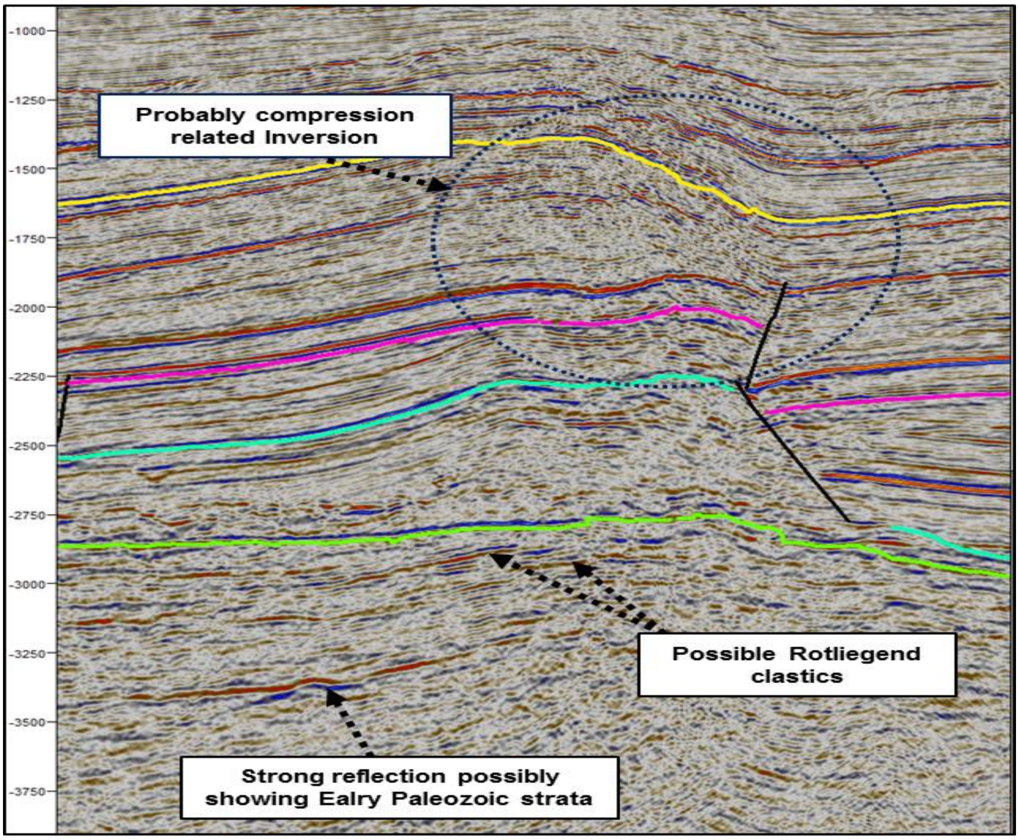


Figure 4.17: Close-up of regional key seismic profile 7, where the possible Rotliegend and the Early Paleozoic strata are observed. On top of it an inversion structure is also seen which is encircled.

4.4. Time-structure (TWT) and fault maps

The time-structure maps and the fault maps are made at four different stratgraphic levels (figs. 4.18, 4.19, 4.20 and 4.21) according to the horizons interpretation. For each stratigraphic level, fault maps and the time-structure maps are displayed together, side by side. Both of the maps are displayed at the same scale (some minor shift along X-axis). This helps in understanding and identifying the color variations in the time structure map at that certain level. Time-structure maps show the structural variations with respect to time (TWT in ms), extent and orientation of different geometries in the study area. This provides us with in-depth details of certain features present within the main structural elements, hence giving more detailed information of the study area. The shallower part is shown by red color (low TWT values) and deeper part is shown by purple color (high TWT values). Location of the key profiles with there numeric order (fig. 4.1) are also shown on these maps for further assistance. The four different stratigraphic levels at which these maps are generated are as follows:

- Base Zechstein (mid-Permian) stratigraphic level.
- Base Triassic stratigraphic level.
- Mid-Jurassic stratigraphic level.
- Base Chalk (mid-Cretaceous) level.

4.4.1. Base Zechstein (mid-Permian) stratigraphic level

There are six main faults present at the Base Zechstein stratigraphic level (fig. 4.18.a). Most of the main faults have NE-SW strike except one main fault (MF6), whose strike is from the N-S. Time-structure map is showing the deeper parts towards SW direction in the Norwegian-Danish Basin and the shallower parts towards SE and NW sides on the Sele High and the Utsira High respectively. The trend varies along the lateral extent of the Ling Depression. The central part of the Ling Depression shows low time values (due to presence of structural highs) but the adjacent sides are showing deeper parts in the Ling Depression. Towards the NE it is gradually getting deeper into the Åsta Graben and towards SW it gets much deeper into the Norwegian-Danish Basin area (fig. 4.18.b).

The fault map (fig. 4.18.a) shows that the Ling Depression area is extensively faulted with the presence of secondary faults. Mostly these faults are following a NE-SW trend. There are few faults in the Ling Depression which are having a N-S trend. Especially on the NE side of the Ling Depression there are two secondary faults having the N-S strike with the same dip direction which is towards the NE. Along the trend of key profiles 5 and 6 on the fault map (fig. 4.18.a), a local high at the Base Zechstein stratigraphic level can be observed which has the NE-SW orientation. The same structure is also shown on the detailed interpretation of Key Profile 6 (see Horst 7 on fig. 4.12.a and 4.14.a). The time-structure map shows low TWT values at the same location. Towards the NE and the SW of this structure (Horst 7) the relatively high TWT values point towards deeper part (low relief area) (fig. 4.18.b). This shows the NE-SW lateral extent of this local structural high within the Ling Depression. Another high relief structure is observed towards the SW of the horst 7 within the Ling Depression. This local structural geometry is not covered by any key profile. But on the fault map towards the SW of local high (Horst 7), two faults with NE-SW extent, having opposite dip directions can be observed. A gentle variation of TWT values in the time-structure map shows that the extent/orientation of this structure is from NE-SW. So both these high-relief structural geometries lie in a NE-SW lateral extent within the Ling Depression. Towards the north of these structures the Ling Depression is gettting deeper which is shown by increasing TWT values on the time-structure map. Then more towards the NW of the Ling Depression, in the Utsira High area, again a gradual shallowing trend can be observed (fig. 4.18.b). The time-structure map only covers the southern flank of the Utsira High because the Base Zechstein reflector was not present there. Small opposing half-graben geometries are also observed in the northern and southern sides of the Horst 7 within the Ling Depression. Time-structure map shows high TWT values at these locations , theerfore representing high relief zone (fig. 4.18.b).

Towards the Sele High, there is less faulting compared to the Ling Depression. As we move from the Ling Depression to the Sele High, we observe abrupt variation in the TWT values on the time-structure map. This is due the presence of another paleo-high (Horst 3). This local structural geometry is interpreted on the key profiles 2 and 7 (see figs. 4.5.b and 4.16.b). The time-structure map is showing the NE-SW orientation of this structure. Further down to the SE direction in central part of the Sele High, the TWT decreases gently but it increases again on the SE edge of the Sele High. This is due to presence of another structural high (Horst 4) which is interpreted on key profile 2 (see fig. 4.5.b). This structure also has a lateral orientation from NE-SW. The south-eastern boundary of this horst structure (Horst 4) is marked by main fault MF6 (fig. 4.18.a). Another most prominent fault observed at the Base Zechstein stratigraphic level on the Sele High has the NNW-SSE strike and dip direction towards the NE. It can be observed on the NW part of the Sele High on the fault map (fig. 4.18.a). Another relatively small but opposing fault is observed on the western side of this fault. These normal faults with opposing dip directions are also making a horst type structure (Horst 6), which is interpreted along key profile 4 (fig. 4.10.b). Towards the SE of time-structure map along key profile 1, two small-scale faults are having opposite dip direction (fig. 4.18.a) and forming a horst type structure (Horst 1) on the Sele High (see fig. 4.3.a). This horst structure is showing a bit high TWT values on the time-structure map as compared to other horst geometries in the study area.

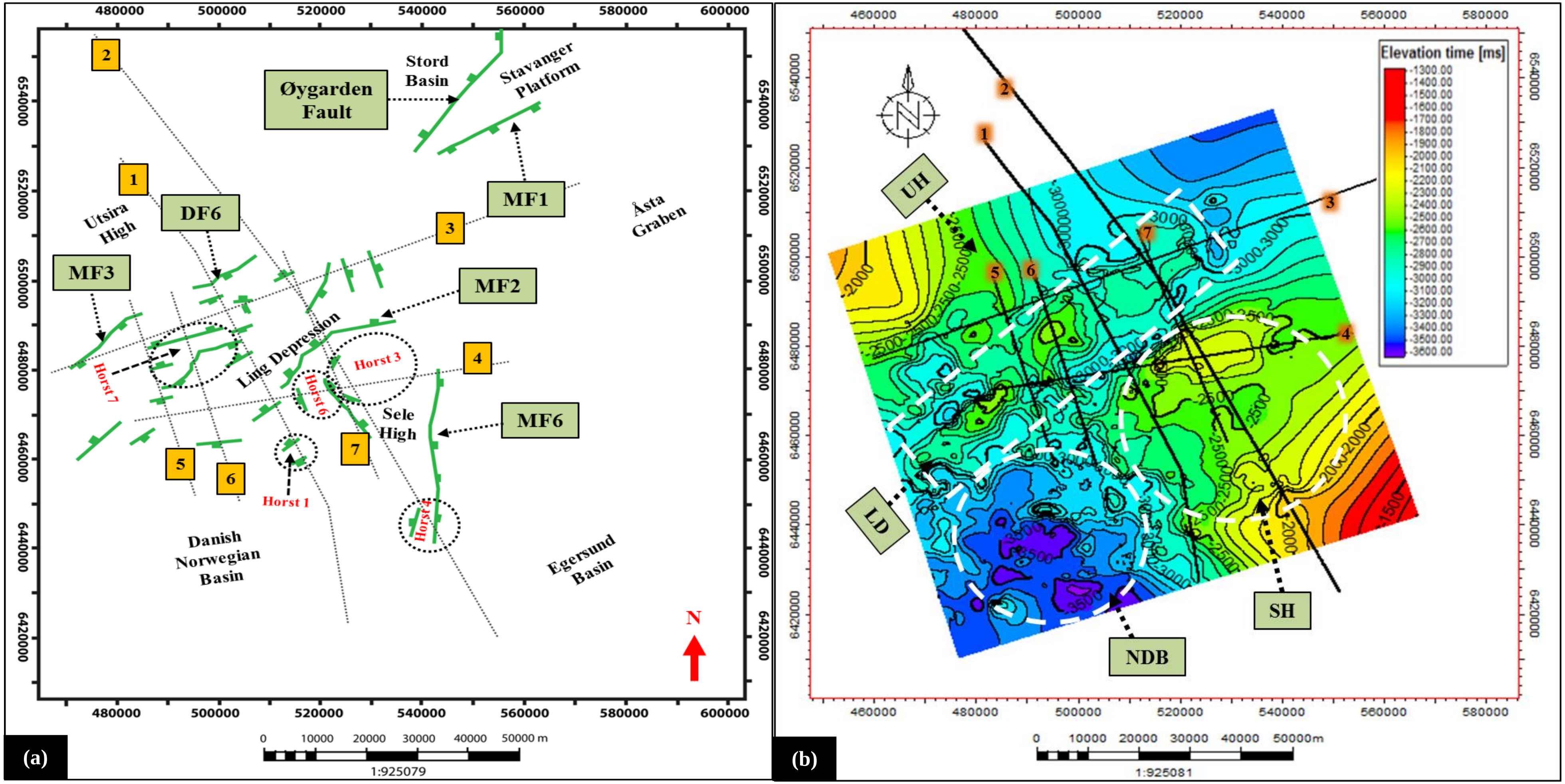


Figure 4.18: **(a)** Fault map of the Base Zechstein stratigraphic level with some local structural elements encircled. Key profiles are given numbers as mentioned in figure 4.1 above. **(b)** Time-structure map at the Base Zechstein stratigraphic level with the key profiles displayed in numeric order. Legend for the color variations with respect to time (ms) is given on upper right corner. SH=Sele High, UH=Utsira High, LD=Ling Depression and NDB=Norwegian- Danish Basin.

4.4.2. Base Triassic stratigraphic level

There are eight main faults present at the Base Triassic stratigraphic level. Some of the main faults have the NE-SW strike, while others have the NW-SE strike direction. Only MF11 has a strike direction of E-W. The trend of time-structure map shows the deeper parts towards the SW and the NE in the Norwegian-Danish Basin and the Åsta Graben respectively. The shallower part is shown by low time values at the Sele High and at some places in the Ling Depression. No observation has been made on the Utsira High as the Base Triassic horizon is not interpreted there. The closed contours at this level have resulted due the presence of salt domes (fig. 4.19.b). They are mostly concentrated in the Norwegian-Danish Basin and at the SW edge of the Ling Depression which is marking the boundary with this basin.

Two main faults, MF5 and MF11 are supposed to have formed in the Early Triassic times as they are not present on the Base Zechstein fault map. These two faults are also the bounding faults in the study area. MF5 separates the Sele High and MF11 is separating the Ling Depression, from the Norwegian-Danish Basin. Overall intensity of faulting at the Base Triassic period is less in the Ling Depression as compared to the Base Zechstein (mid-Permian) period. But mostly the trend is similar which is from the NE-SW (fig. 4.19.a). If we look at the time-structure map (fig. 4.19.b), it clearly shows low time values (TWT in ms) in the central part of the Ling Depression along its lateral extent (which is NE-SW) but the increase in TWT towards its south-eastern side shows the deepening trend, forming a depression like geometry. The fault map of the Base Triassic stratigraphic level shows, opposing fault geometries in the cental part of the Ling Depression, which have probably resulted in the uplifted structures (fig. 4.19.a). This trend is followed along the extent of the Ling Depression. These structural geometries are interpreted on seismic key profile 2 which is crosscutting these features (see fig. 4.5.a). Towards the SW in the Ling Depression, a structural high is formed by the two main faults (MF9 and MF11) which have opposite dip directions (fig. 4.19.a). There are two large salt domes present on this structural high just at the boundary of the Ling Depression and the Norwegian-Danish Basin (fig. 4.19.b).

The Sele High is quite prominent in the time-structure map (fig. 4.19.b) at this stratigraphic level. While moving from the north to south across the Ling Depression, as soon as we cross MF2, there is sudden variation in time values (TWT in ms) observed on time-structure map. The time values change from high to low, due to change in elevation. This is marking the boundary between the Ling Depression and the Sele High on a time-structure Map (fig. 4.19.b). Towards the NE in the Åsta Graben, an abrupt change in the time values represent the deeper part. Closed contours can be seen on the SW side in the Norwegian-Danish Basin. These are formed due salt halokinesis, which have resulted in large salt domes in this area. The Norwegian-Danish Basin also shows the deeper parts on the time-structure map (fig. 4.19.b).

4.4.3. Mid-Jurassic stratigraphic level

There are eight main faults present at the mid-Jurassic level (fig. 4.20). DF6, which separates the Ling Depression from the Utsira High, has disappeared at this level. The lateral extent of MF3, which also separates the Ling Depression from the Utsira High, has decreased to several degrees at this stage (fig. 4.20.a). This shows that the intensity of the NE-SW trending faults have decreased during this time period. MF6, which is the eastern boundary fault of the Sele High, has again appeared on the fault map (fig. 4.20.a). This was not traced at the Base Triassic stratigraphic level (fig. 4.19.a), probably due to presence of salt. It is possible that this fault was either active throughout Permian to mid-Jurassic times or it again got reactivated at this stage. The trend on time-structure map shows deeper parts in the SW towards the Norwegian-Danish Basin, in the NE towards the Åsta Graben and in the northeastern lateral extent of the Ling Depression. Further towards the NE trend changes to shallow. In the NW and SE, we can clearly observe the shallower trend due to presence of the Utsira High and the Sele High (fig. 4.20.b).

The intensity of faulting has decreased in the Ling Depression to certain degree on the northeastern edge probably due to halting of the NE-SW trending faults (fig. 4.20). Similar horst-graben geometries are observed in the central part of the Ling Depression with deepening of area towards the NW and SE of it. The comparison between the fault map and the time-structure map clearly show the orientation and the extent of the structural geometries in the central part of the Ling Depression (fig. 4.20). As we move along the Ling Depression from the NE to the Norwegian-Danish Basin in the SW, the depth increases. The high time values (TWT in ms) towards the SW marks the transition from the Ling Depression to the Norwegian-Danish Basin, which is deeper due to its basinal geometry. While moving to the NE direction along the Ling Depression into the Åsta Graben, clear increase in depth is observed. If we follow trend of key profile 3 in the NE direction on the time-structure map (fig. 4.20.b), we can see structurally low relief area showning high TWT values. This is a nice depression which can be observed on interpreted key profile 3 (fig. 4.7.a).

Towards the Sele High, we can see some faulting in the SE direction. Three secondary faults, synthetic to each other, are developed on the SE edge of the Sele High. They have the NW dip direction. A clear variation in time values can also be observed on the time-structure map at the same location. TWT values changes from high to low on the Horst 4 (fig. 4.20.a and b**)**. As we move from the Ling Depression to the Utsira High, a gradual increase in TWT values is observed (fig. 4.20.b).

4.4.4. Base Chalk (mid-Cretaceous) stratigraphic level

Most of the main faults have disappeared or their extent has decreased at the Base Chalk stratigraphic level (fig. 4.21.a). Six main faults are present at this stratigraphic level. The two main faults (MF3 and DF6) separating the Ling Depression from the Utsira High have totally vanished. MF6 is also not present at this stratigraphic level, which was separating the Sele High from the Egersund Basin and the Åsta Graben in the SE. The NE-SW extension of MF1, which was marking the northern limit of the Zechstein salt basin during the Late Permian times, has also disappeared. Due to which the extent of MF1 has decreased at large scale. The E-W trending right limb of MF2 is also not present at this stratigraphic level. The fault map of mid-Cretaceous hence shows much stable tectonic settings. Only one main fault (MF7) with the NW-SE strike, has been formed during mid-Cretaceous period in the Norwegian-Danish Basin which has opposite dip direction to MF5 which separates the Sele High from this Basin (fig. 4.21.a). If we correlate the fault map of the mid-Cretaceous stratigraphic level with its time-structure map, we can determine that the tectonic settings were quite stable at this time. The time-structure map shows a nice and simple trend of shallowing to deepening from the NE to the SW (fig. 4.21.b). This variation in elevation from the NE to the SW can be clearly observed along the strike of key profiles 3 and 4 (figs. 4.7.a and 4.10.a).

Same fault trends and geometries are observed in the Ling Depression with much less intensity. Along the SE strike of key profile 2 on the fault map, where key profile 2 and 7 crosscut each other (fig. 4.21.a), a local depression is observed within the Ling Depression (see also fig. 4.5.a). On the fault map we can see a secondary fault with the SE dip direction, from where this local depression is starting. This fault has opposite dip direction to MF2 (fig.

4.21.a). For further verification of this local structure we can clearly see the variations in TWT values on time-structure map at the same location (fig. 4.21.b).

Along the NW-SE lateral extent of the Sele High, we can see the shallowing trend towards the SE and deepening trend towards the NW (fig. 4.21.b). A fault map also shows that the faults are dipping in NW direction on the Sele High area. On the Utsira High we have a decrease in elevation, which shows it with high time values (TWT in ms) on the time-structure map.

4.5. Time-thickness maps

Time-thickness map helps us to determine the thickness variations between certain stratigraphic levels with respect to time (ms) and gives information on the depocenter (area of maximum thickness) and structural inversion. Two time-thickness maps have been generated during the study which are as follows:

4.5.1. Late Permian (Zechstein salt) time-thickness map

The time-thickness map of the Late Permian group helps us determine the variations in thickness of salt at different places within study area. On the NE and the SE sides of the Sele High we can see that salt is totally absent or eroded. This is probably due to the presence of structural highs at this area in the Late Permian time (fig. 4.22). As on the fault map of the Base Zechstein stratigraphic level we can see the horst structures developed at these locations of the Sele High (fig. 4.18.a). There is a thin salt layer present on the central part of the high but on the SW edge of the Sele High, there is increased value of thickness represented by high TWT values. The salt is almost absent on the Utsira High, probably because the Zechstein sea during the Late Permian times did not transgress into that part of the study area. But minor level of salt is present on the southern edges of the Utsira High (fig. 4.22). The salt group has varying thickness in the Ling Depression. It is thicker towards the NW along the lateral extent of the Ling Depression but thinner towards the SE. The closed contours in the Ling Depression and the Norwegian-Danish Basin were probably the result of sudden increase in thickness as a presence of salt diapirs. Maximum thickness of the Late Permian salt group is observed in Norwegian-Danish Basin and probably it is representing a depocenter for the Late Permian salt (fig. 4.22). There is a lot of variation in TWT values observed in time-thickness map of Zechstein salt group. It is difficult to indicate a primary depocenter on the salt time-thickness map. But the time-structure maps (fig. 4.18.b,4.19.b, 4.20.b and 4.21.b) show low relief area towards the Norwegian-Danish Basin and if compared with the salt time-thickness map (fig. 4.22), it can probably be assumed that the depocenter was in the Norwegian-Danish Basin during the Ealry-Late Permian times.

4.5.2. Time-thickness map from mid-Jurassic to Base Chalk

Time-thickness map between the Base Chalk and the mid-Jurassic stratigraphic levels help us determine the variation in thickness in the study area. A general trend of increase in thickness can be observed on the map. The thickness is increasing from the SW to the NE (fig 4.23). Minimum thickness is observed on the Utsira High and the SW part of the Ling Depression. The thickness of this unit is higher on the Sele High and in the Norwegian-Danish Basin. Maximum thickness is observed in the Åsta Graben area and it is probably representing a depocenter of that time (fig 4.23). Time-thickness map shows relatively gradual increase in the TWT values towards the NE. It is possibly due to rather stable conditions between these time periods in the study area.

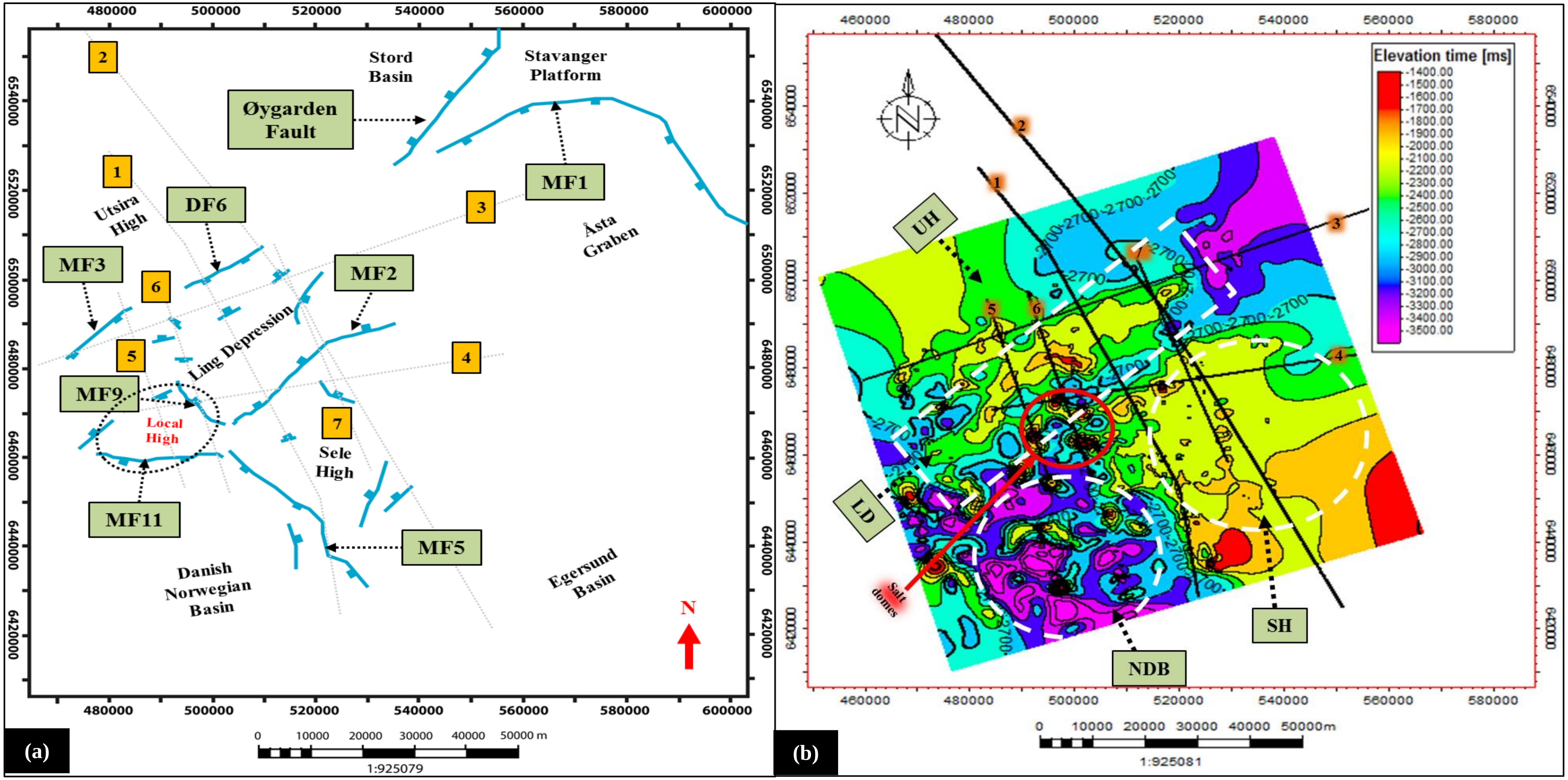


Figure 4.19: **(a)** Fault map of the Base Triassic stratigraphic level with local structural high encircled. Key profiles are given numbers as mentioned in figure 4.1. **(b)** Time-structure map at the Base Triassic stratigraphic level with the key profiles displayed in numeric order. Red circle is showing major salt domes in the study area. Legend for the color variations with respect to time (ms) is given on upper right corner. SH=Sele High, UH=Utsira High, LD=Ling Depression and NDB=Norwegian-Danish Basin.

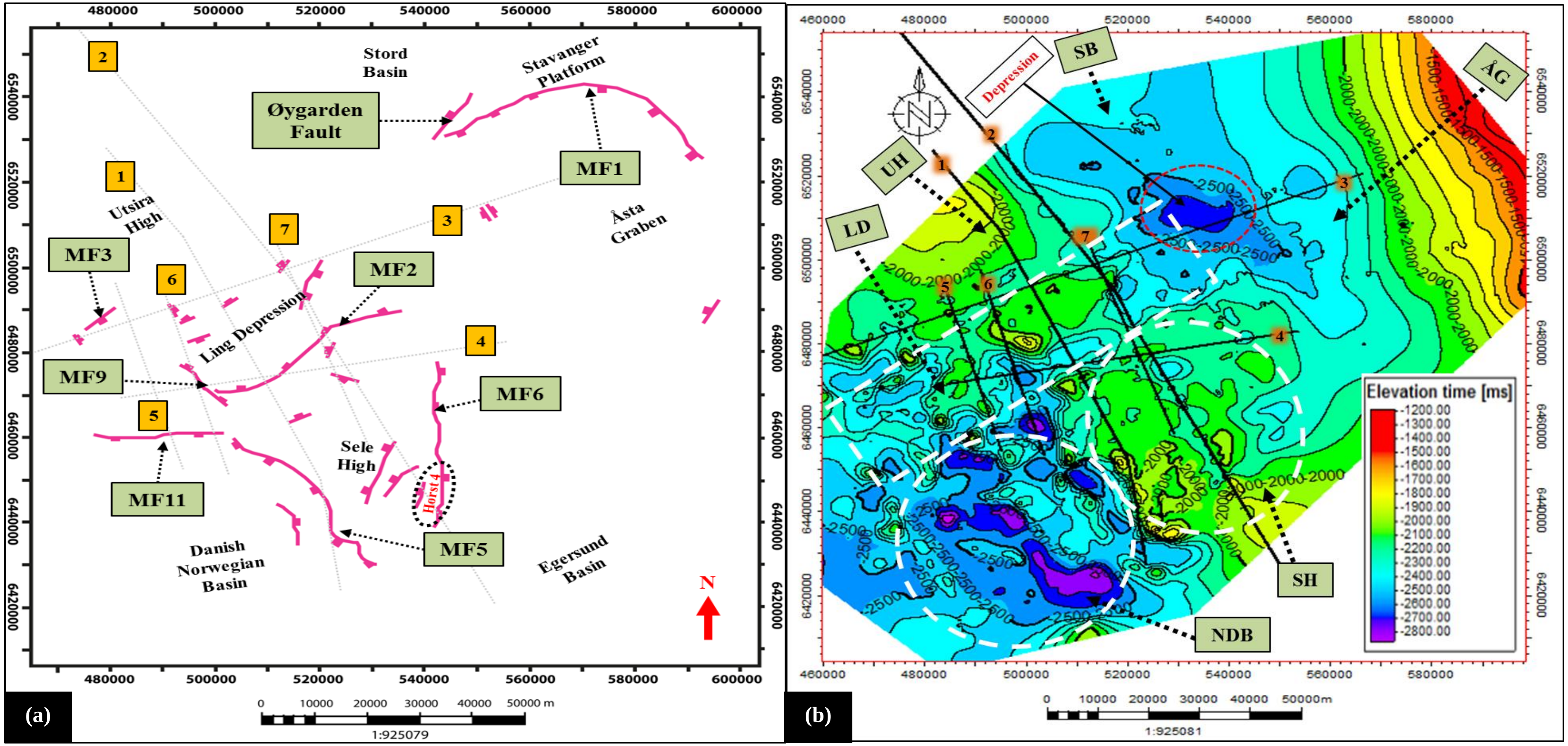


Figure 4.20: **(a)** Fault map of the mid-Jurassic stratigraphic level with local structural feature (Horst 4) encircled. Key profiles are given numbers as mentioned in figure 4.1. **(b)** Time-structure map at the mid-Jurassic stratigraphic level with the key profiles displayed in numeric order. Red circle is showing a depression in the study area. Legend for the color variations with respect to time (ms) is given on upper right corner. SH=Sele High, UH=Utsira High, LD=Ling Depression, SB=Stord Basin, ÅG=Åsta Graben and NDB=Norwegian-Danish Basin.

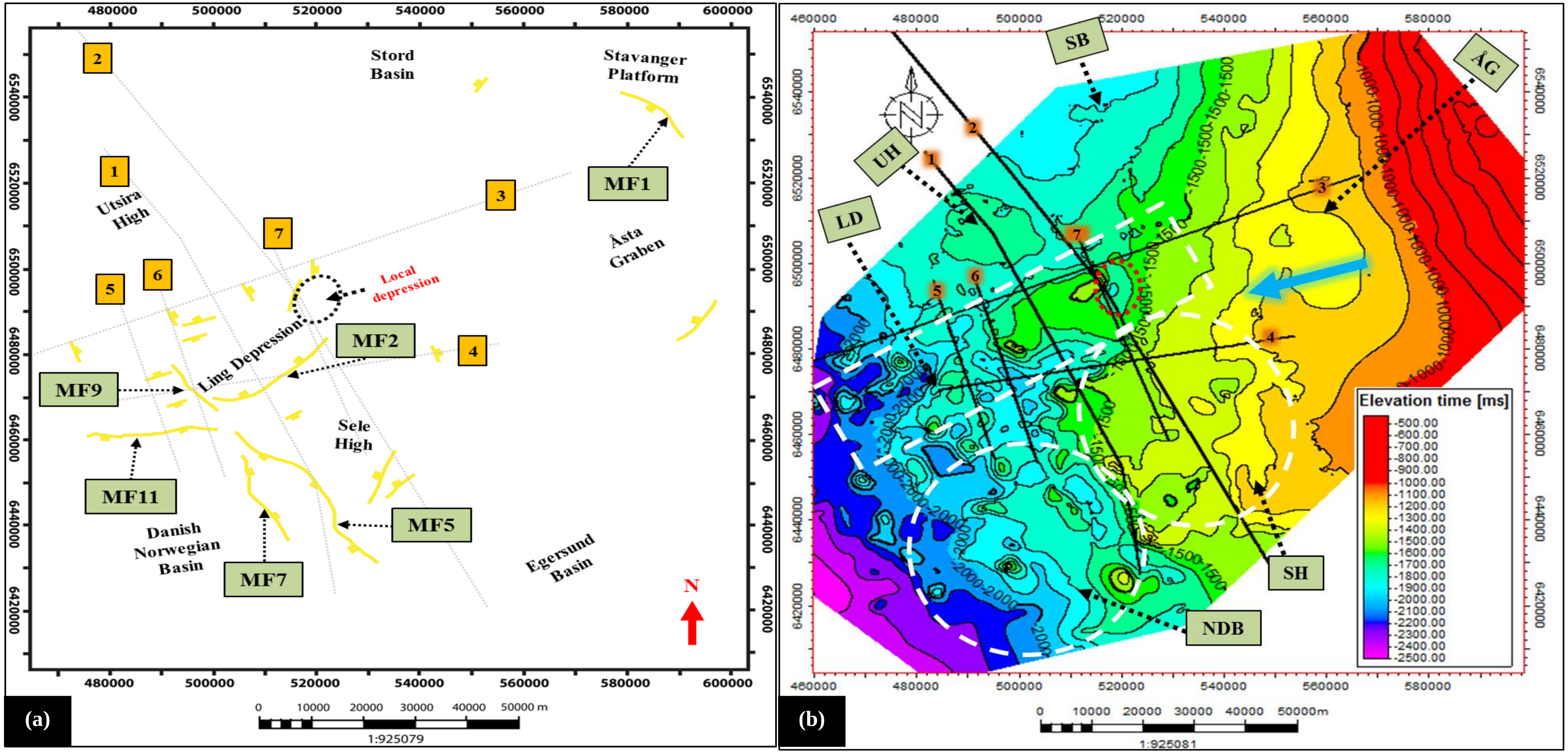


Figure 4.21: (a) Fault map of the Base Chalk (mid-Cretaceous) stratigraphic level with local structural feature encircled. Key profiles are given numbers as mentioned in figure 4.1. **(b)** Time-structure map at the Base Chalk (mid-Cretaceous) stratigraphic level with the key profiles displayed in numeric order. Red circle is showing a local depression in the Ling Depression. Blue Arrow is showing a trend from shallow to deep. Legend for the color variations is given on upper right corner. SH=Sele High, UH=Utsira High, LD=Ling Depression, SB=Stord Basin, ÅG=Åsta Graben and NDB=Norwegian-Danish Basin.

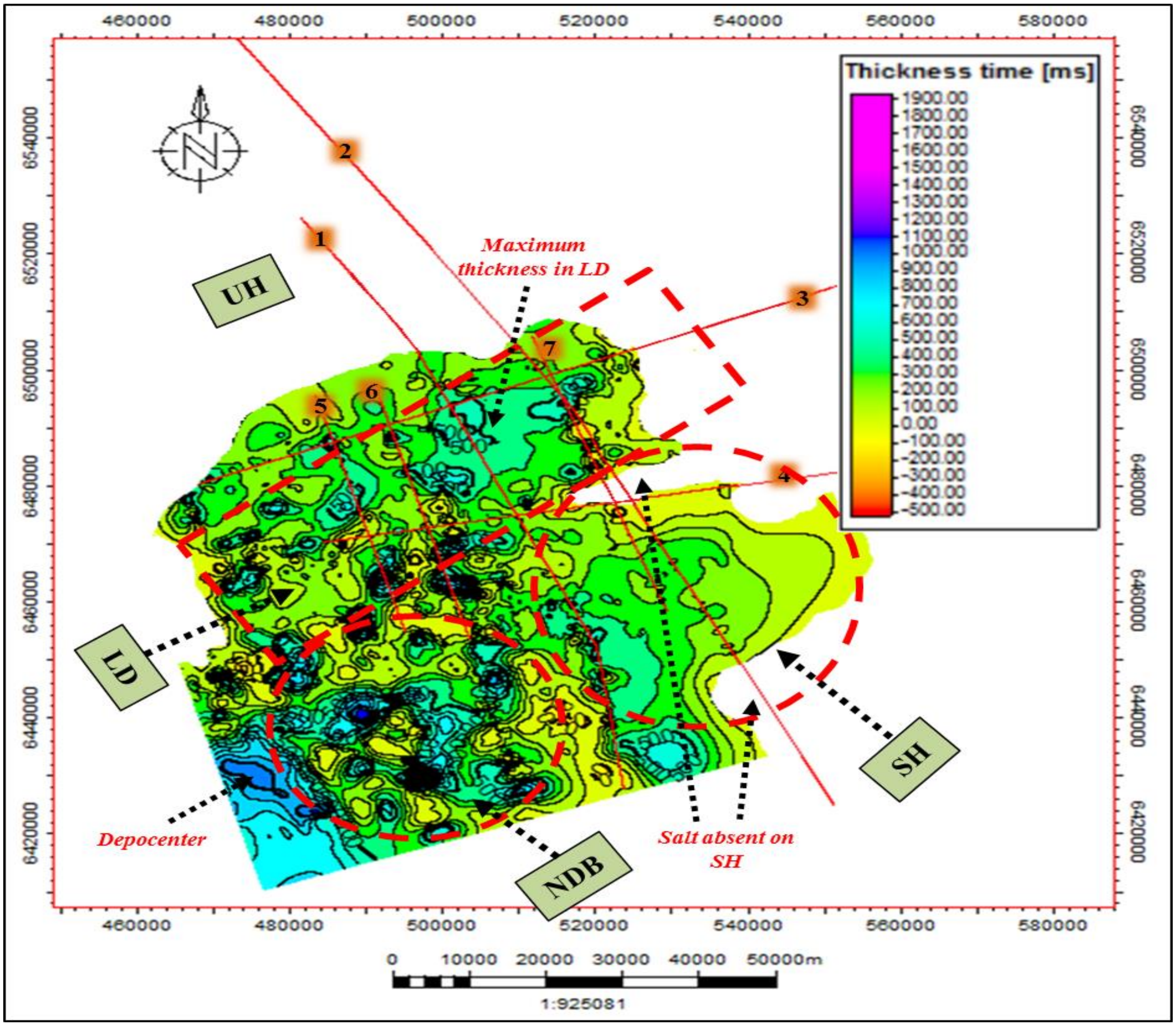


Figure 4.22: Late Permian (Zechstein salt) time-thickness map with the location of key profiles in numeric values (see fig. 4.1). It is also showing the Depocenter. The legend for the color variations with respect to the change in TWT values is given in the upper right corner. UH=Utsira High, LD=Ling Depression, SH=Sele High and NDB=Norwegian-Danish Basin.

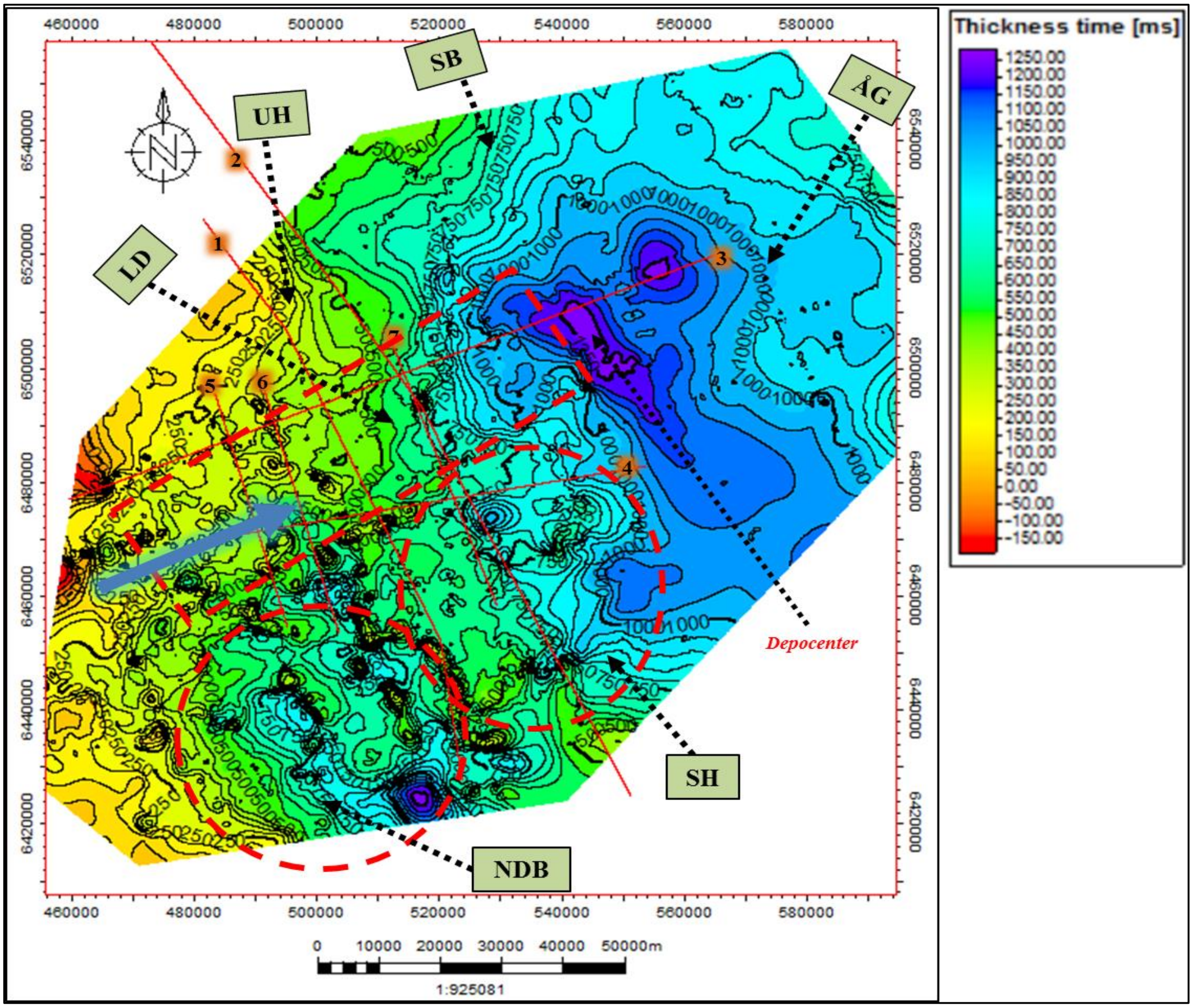


Figure 4.23: Time-thickness map from the mid-Jurassic to the Base Chalk horizon with the location of key profiles in numeric values (see fig. 4.1). It is also showing the Depocenter. The legend for the color variations with respect to the change in TWT values is given in the upper right corner. Blue arrow shows general trend of increase in thickness towards the NE. LD=Ling Depression, UH=Utsira High, SH=Sele High, NDB=Norwegian-Danish Basin, SB=Stord Basin and ÅG=Åsta Graben.

CHAPTER 5

DISCUSSION

Several tectonic episodes have shaped the North Sea basin. The regional tectonic episodes which are well documented around the North Sea from Devonian to Cretaceous are as follows:

- Devonian extension causing the formation of large shear zones following a NE-SW trend (Fossen, 1992).
- Late Carboniferous-Early Permian stretching of the crust causing wrench faulting and rifting along E-W direction, resulting in the formation of half-graben structures (Ziegler, 1990; Heeremans and Faleide, 2004).
- NW-SE to WNW-ESE directed extension occurring in the Late Jurassic which is represented by NNE-SSW structural orientation (Smethurst, 2000).
- Late Cretaceous inversion of earlier formed extensional structures due to reactivation of faults (Ziegler, 1990).

All these main events and trends are observed during this study (see fig. 4.2). Composite fault map shows lateral variations in the area which helps in understanding and visualizing the main fault trends. Detailed analysis and description of key profiles were carried out in chapter 4 with respect to fault patterns, structural geometries and stratigraphy. The main tectonic events along with some key features observed during this study are to be discussed in more details, in order to understand the geological evolution of the Ling Depression and its adjacent highs.

5.1. Devonian extensional event

A major event of extension occurred during the Early Devonian along a NE-SW direction, which produced large ductile shear zones (Fossen, 1992). One of the important ductile shear zones which have shaped the architecture of the North Sea is Hardangerfjord Shear Zone. The Lærdal-Gjende Fault system which was most probably formed in the Late Devonian marks the brittle continuation of Hardangerfjord Shear Zone. In the SW towards offshore region, the strain caused by the stresses that generated Hardangerfjord Shear Zone may have been accommodated by other deeply-rooted NE-SW trending faults (Fossen and Hurich, 2005). These brittle faults are most likely running down into the basement (Færseth, 1996) and are genetically linked with Hardangerfjord Shear Zone.

Some deep-rooted faults are observed in the study area, which presumably represent the brittle continuation of the Hardangerfjord Shear Zone in the offshore region. These deep faults have formed large horst structures. Horst structures were interpreted in some parts of the Ling Depression and the Sele High (fig. 4.18.a). One of the most prominent and large-scale horst structures (Horst 7) was observed on key profiles 5 and 6 (see figs. 4.12 and 4.14) within the Ling Depression. It is bounded by two large faults which are running deep into the crust. Another main structural feature, which presumably forms a link to the basement shear zone, is fault DF6 (see figs. 4.3 and 4.5). A large tilted fault block was also interpreted which is bounded by the deeply-rooted faults having ENE dip direction (see figs. 4.10 and 4.11). All these structures are perhaps related to the Devonian extensional event.

5.2. Late Carboniferous-Early Permian rifting event

Rotated half-graben structures were observed below the Base Zechstein during this study (see fig. 4.3). These tilted half-graben structures are pointing towards a major rifting event. Heeremans and Faleide (2004) suggested the presence of Rotliegend half-grabens below the Base Zechstein in the Ling Depression on the basis of their seismic interpretations and data from the surrounding area, which are formed by E-W oriented extensional movements that caused major rifting in Late Carboniferous-Early Permian. These possible Rotliegend half-graben of Late Carboniferous-Early Permian, are interpreted within the Ling Depression on almost all the key profiles. Lateral continuity of these half-grabens is observed throughout the Ling Depression along key profile1 (see fig. 4.3).

5.2.1. Linked half-grabens within the Ling Depression

The NE-SW oriented fault geometries at the Base Zechstein stratigraphic level represent opposing half-graben structures with shifting polarities along strike (fig. 5.1). These opposing structures form the linking family of half-grabens. These types of zones are indicative of strike-slip motion (Rosendhal, 1987). The Ling Depression may have a genetic link to the Midland Valley which was formed in strike-slip settings (Heeremans and Faleide, 2004). The Midland Valley is bounded by the Highland Boundary Fault on the NE which is a major sinistral strike-slip fault (Marshall and Hewett, 2003). The Ling Depression lies on a trend of the Highland Boundary Fault (see fig. 2.6). Therefore, the strike-slip element is inherited most probably from this fault which perhaps forms a genetic link with the Hardangerfjord Shear Zone (see fig. 2.6). But no strong argument can be setup due to lack of data regarding the genetic link of the Highland Boundary Fault and the Hardangerfjord Shear Zone. Further studies need to be carried out in this case.

5.2.2. Syn-rift and post-rift transition during the Late Permian

Thermal relaxation and subsidence at the end of the Early Permian resulted in formation of the Permian salt basins (Northern and Southern Permian basins) where the Zechstein salt was deposited (Heeremans and Faleide, 2004) (see fig. 2.3). The base of the Zechstein Group marks a regional unconformity between syn-rift and post-rift deposits (Ziegler, 1975). Most of the faults which formed due to Late Carboniferous-Early Permian crustal stretching and rifting became inactive during the Late Permian**.**

The Base Zechstein in the study area is probably representing a transition from syn-rift to post-rift stage. The possible Rotliegend reflectors are truncated by the Base Zechstein horizon at some places, therefore marking a local unconformity (fig. 5.2). No major rifting event is observed during the Zechstein salt deposition (Late Permian). Therefore, the Late Permian time period likely represents overall stable conditions.

5.3. Triggering of the Zechstein salt in the Triassic

The Northern and Southern Permian basins continued to subside during the Triassic. The increasing subsidence along with increase in sedimentation rates resulted in thick accumulation of Triassic sediments. In the Central North Sea, the thick accumulation of the Triassic deposits triggered the salt movement during the Middle and Late Triassic, therefore forming the large salt diapirs (Ziegler, 1978). Large salt diapirs have also been observed on key profiles 4, 5 and 6 (see figs. 4.10, 4.12 and 4.14).

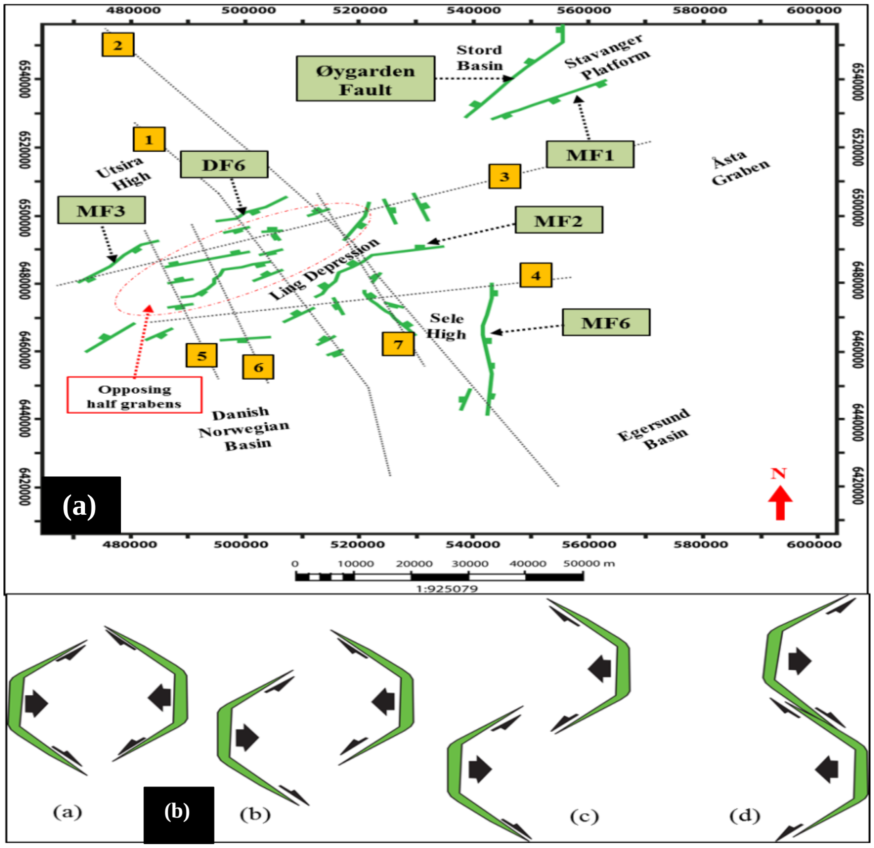


Figure 5.1: (a) Fault map of the Base Zechstein stratigraphic level. Opposing half-grabens are encircled in red. Key profiles are given numbers as mentioned in figure 4.1. **(b)** Architecture of overlapping opposing half grabens (a-c) and non-overlapping opposing half graben (d) (modified from Rosendhal, 1987).

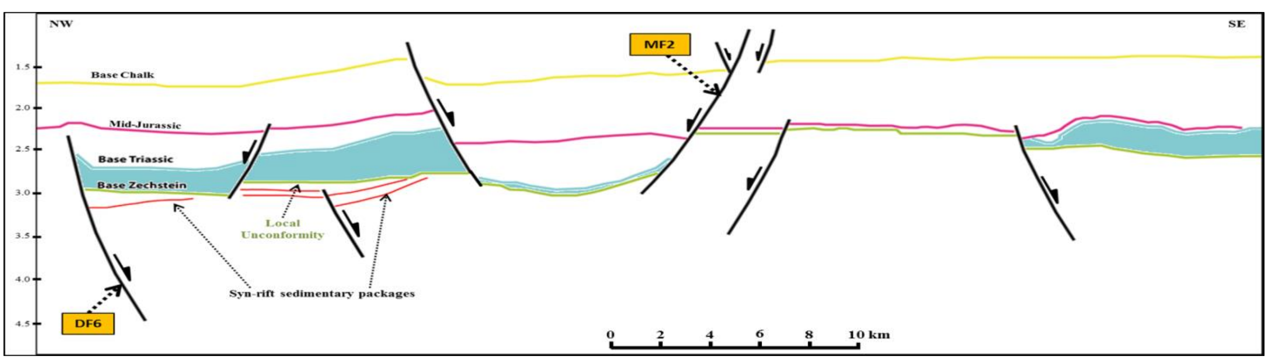


Figure 5.2: The underlying strata (probably Rotliegendes) is terminating into the Base Zechstein horizon, therefore marking a transition between syn-rift and post-rift deposits. Blue color-fill is representing the Zechstein salt deposits. This line drawing is taken from key profile 2 (see fig. 4.5).

5.4. Late Jurassic rifting event

In the Central North Sea, a large rift dome associated with volcanism was developed during the Early-mid Jurassic (Ziegler, 1978; Graversen, 2005). Crest of this dome was transected at the triple junction, formed by the Southern Viking Graben, the Central Graben and the Moray Firth Basin (see fig. 2.6). This triple junction acted as a volcanic center at that time (Howitt et al., 1975; Gibb and Kanaris-Sotirious, 1976). During the Middle and Late Jurassic, discrete rift phases affected NW-Europe (Ziegler, 1975). NW-SE to WNW-ESE directed extension caused a major rifting event in the Late Jurassic and developed NNE-SSW oriented structures (Smethurst, 2000).

The time-thickness map between the mid-Jurassic and the Base Chalk shows the depocenter towards the Åsta Graben area (see fig. 4.23) which provides evidence that this graben was formed during the Late Jurassic as a result of this major rifting event.

The Late Jurassic rift phase is well documented in the North Sea. It is proposed by Heeremans and Faleide (2004), that the large offsets observed on the Base Zechstein horizon are to some extent due to the Mesozoic rifting. Perhaps the offset at the Base of Zechstein deposits observed on the key profiles is partly a result of this younger rifting event (fig. 5.3). These offsets are representing local rift structures in the study area. Zechstein salt also functioned as a buffer or detachment layer, which mostly separates the pre-Zechstein structures from the post-Zechstein structures in the area under consideration.

5.5. Inversion during the Late Cretaceous

During the Alpine compression phase in the Late Cretaceous, inversion tectonics was active in some parts of the North Sea which resulted in the reactivation of pre-existing faults and structures (Ziegler, 1975). The structurally inverted features such as monoclines and inverted faults are observed in the seismic sections at the Base Chalk stratigraphic level (Upper Cretaceous).

5.5.1. Alpine compression and salt movement

At shallower levels, the compressional features developed probably due to the Alpine compression in the study area. However, the role of salt cannot be ruled out either, as the salt movement affected the local thickness of the strata. Large salt diapirs have been observed which have vertically penetrated the younger sedimentary units; hence generating faults at shallower levels (see figs. 4.10.a, 4.12.a & 4.14.a). The salt tectonics has mostly inverted the stratigraphy above the Base Chalk horizon probably of the Cenozoic age which is not confined to this study. Salt tectonics remained active during the Cenozoic period (Stewart and Coward, 1994).

Two monoclinal structures in the study area most likely formed due to the Alpine compression are shown in figure 5.4. These structures are displaying positive inversion, as the extensional fault movements have been reversed presumptively during the regional compressional tectonics (fig. 5.4.a). In the positive inversion case, individual faults may sustain extensional features in the depth and show contractional features, such as anticline or monocline, in the shallower part (fig. 5.4.c) (Williams et al., 1989). The thick Zechstein salt succession of the Upper Permian is present below the Base Triassic (fig. 5.4.b). The salt has extruded from the SE to probably form this thick halite sequence but it is apparently undisturbed by halokinesis.

The above discussion unveils that the widespread inversion in the study area probably occurred due the regional Alpine compressional stresses during the Late Cretaceous. The role of the Zechstein salt perhaps does not satisfy the development of these large inverted structures during the Late Cretaceous but it may have played role in some local small-scale inversion structures, like folding induced by salt movements, in the study area.

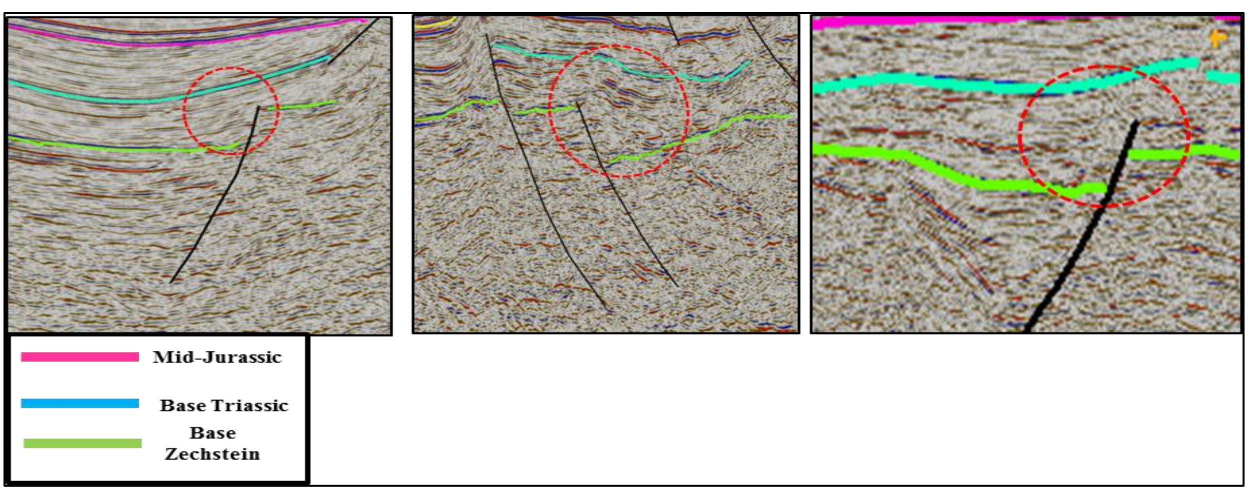


Figure 5.3: A clear offset at the Base of Zechstein is observed. This probably represents a younger rift event probably the Late Jurassic rifting.

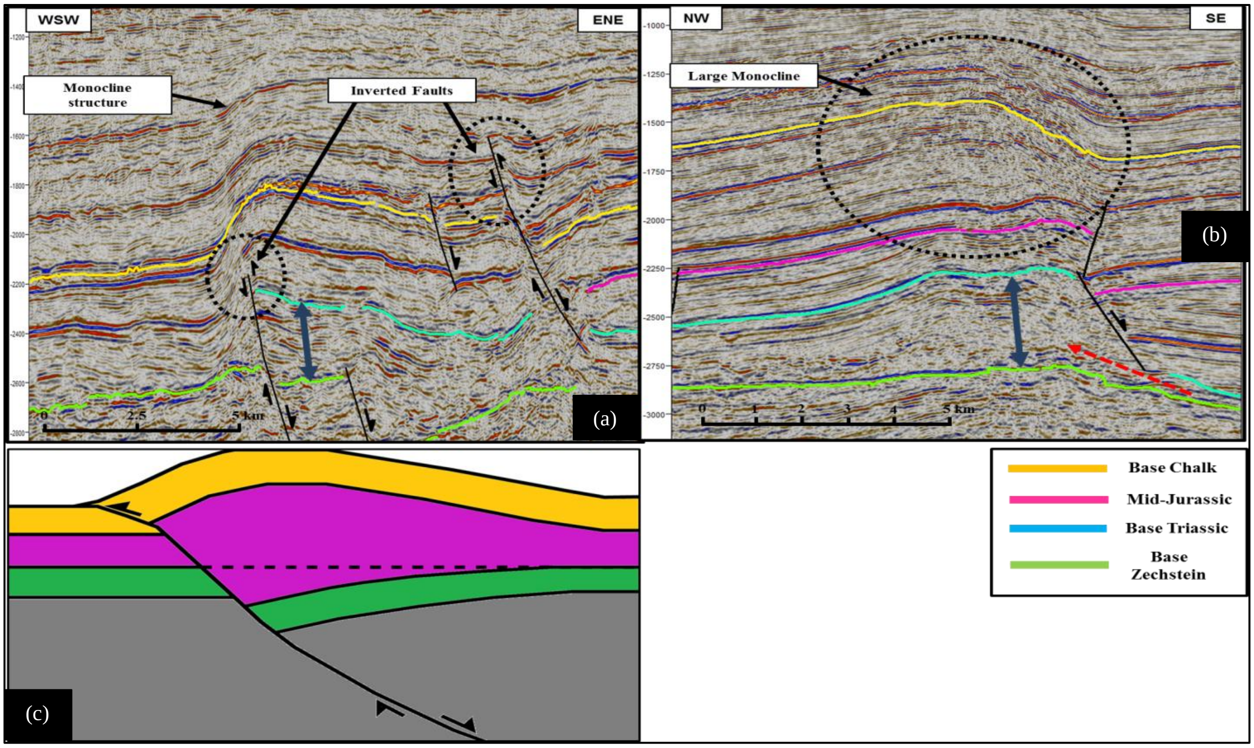


Figure 5.4: (a) Close-up of key profile 3 showing inverted faults movement and the monocline structure, **(b)** Close-up of key profile 7 showing a large monocline at the Base Chalk stratigraphic level. This compressional structure shows inversion during the Late Cretaceous. Red arrow shows direction of the salt extrusion from SE to NW, and **(c)** Positive inversion model (modified from Williams et al., 1989).

5.6. Architecture and role of deep faults in the study area

Deep-rooted faults were interpreted throughout the study area. They have a great role in structuring the brittle crust and introducing complex geometries. Mostly the horst structures observed on key profiles (see chap.4) are formed by the deep-rooted faults. The lateral extent of these structural geometries is observed on the Base Zechstein fault map (fig. 4.18.a)

A large horst structure (Horst 7) most likely resulted from faulting which occurred in the brittle crust as a strain accommodation of the ductile shear zone (Hardangerfjord Shear Zone) during the Late Devonian. The lateral extent of this local horst is from the NE-SW which is similar to the trend of the Ling Depression and the Hardangerfjord Shear Zone which is present beneath it. The vertical displacement of the two opposing faults bounding this horst structure (Horst 7) is greater along the SE dipping faults (fig. 5.5). It is cutting deep reflections presumably of the Early Paleozoic or Top Basement. A NW dipping fault of the Horst 7 cuts through the possible Rotliegend Group. These deep faults are presumptively forming a link with the basement shear zone.

5.6.1. Local inversion in the Late Devonian-Early Carboniferous

A large tilted fault block bounded by the deep-rooted faults was observed on the Sele High during the interpretation of key profile 4 (fig. 5.6.a). Most likely the reflectors in this tilted fault block are of pre-Permian age truncated by another reflector lying straight on top of them. Another interpreted seismic section from the Sele High is showing the same structure as observed during the study, along with the ages assigned to the deep reflections (Marshall and Hewett, 2003) (fig. 5.6.b). They interpreted the Lower Devonian stratigraphy and the possible top Basement which are truncated by the Top Devonian horizon. The Variscan Orogeny caused reactivation of the Devonian extensional faults during the Late Devonian-Early Carboniferous. This compressional tectonic event probably caused inversion of the Devonian extensional faults therefore producing compressional structures (Enfield and Coward, 1987; Séranne, 1992; Underhill and Brodie, 1993).

The bounding faults of this tilted fault block, which are most likely rooting deep into the basement, are representing the brittle continuation of the ductile shear zone as a result of the Devonian extensional event. But probably afterwards in the Late Devonian-Early Carboniferous, it got structurally inverted as a result of the Variscan compressional tectonics. A synclinal structural form is observed on the WSW of this tilted fault block (fig. 5.6). This inversion event is not well documented and detail studies must be carried out in order to fully understand this tectonic event in the Northern Permian Basin.

5.6.2. Reactivation of deep faults during later rift events

These brittle deep faults have been reactivated during the different rift events occurring later in the area. Færseth (1996) proposed that the NE-SW trending faults possibly root down to the Caledonian Basement which got reactivated during the different extensional events occurring later in the North Sea.

An active rift stage has been determined during the Late Carboniferous-Early Permian times (Heeremans and Faleide, 2004). This rifting presumably reactivated the basement controlled faults. One of these basement faults is bounding the Utsira High which is DF6 (fig. 4.2). A sedimentary wedge is developed in its hanging wall below the Base Zechstein (fig. 5.7.b). This perhaps point towards reactivation of this Devonian extensional fault during the Late Carboniferous- Early Permian rifting event.

A large offset is seen at the Base of Zechstein deposits which probably suggest that these deep brittle faults of probably the Devonian extension were reactivated during the Late Jurassic rifting event (fig. 5.5.a, also see fig. 5.3). Heeremans and Faleide (2004) suggested that the large offsets at the Base Zechstein are related to Mesozoic faulting activity. A Permian age is proposed by Andersen et al. (1999) for the reactivation of the brittle Lærdal-Gjende fault which was formed by the continuation of the ductile shear zone (Hardangerfjord Shear Zone) into brittle part of the crust. DF6 is supposed to be reactivated again during the Mesozoic rifting. A normal drag along DF6 is observed in figure 5.7. In the extensional tectonic settings a normal drag along the extensional normal faults is developed when the upward propagating fault breaches the fold on top of it, hence forming a syncline in the hanging wall and anticline in the foot wall (Willsey et al., 2002). The folds in the study area were possibly formed by the salt movements during the mid-Late Triassic due to increase load of the Triassic sediments. Later on in the Late Jurassic rifting, DF6 presumably has been reactivated again and breached the salt induced folding on top of it, therefore resulting in normal drag.

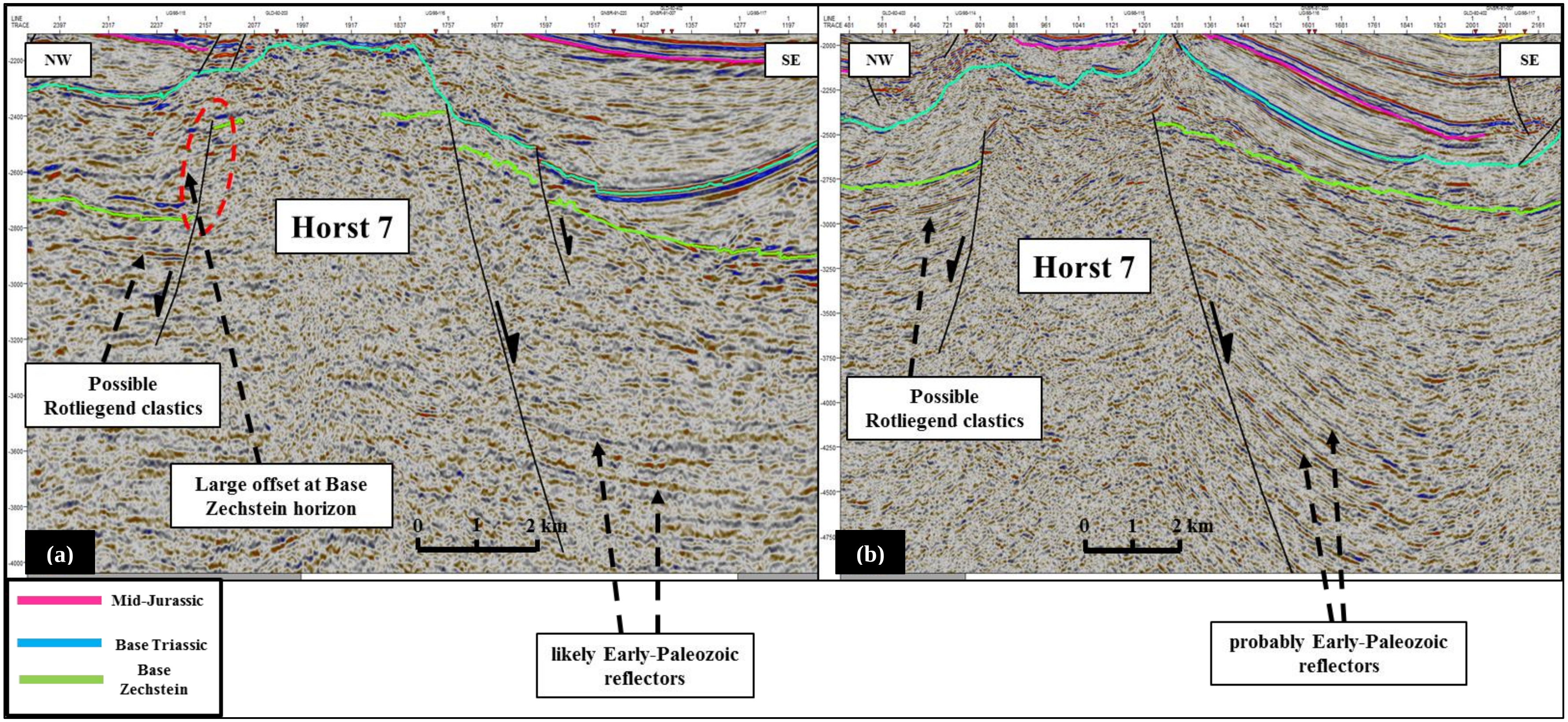


Figure 5.5: Horst structure (Horst 7) in a section view bounded by deeply rooted faults. (**a**) The SE dipping fault is cutting the possible Early Paleozoic reflectors (zoomed portion of key profile 5). Large offset is observed at the Base of Zechstein deposits encircled in red probably resulted due to the Mesozoic rifting and (**b**) The SE dipping fault have greater throw (approx. 4750ms TWT) and is cutting the possible Early Paleozoic reflectors (zoomed portion of key profile 6).

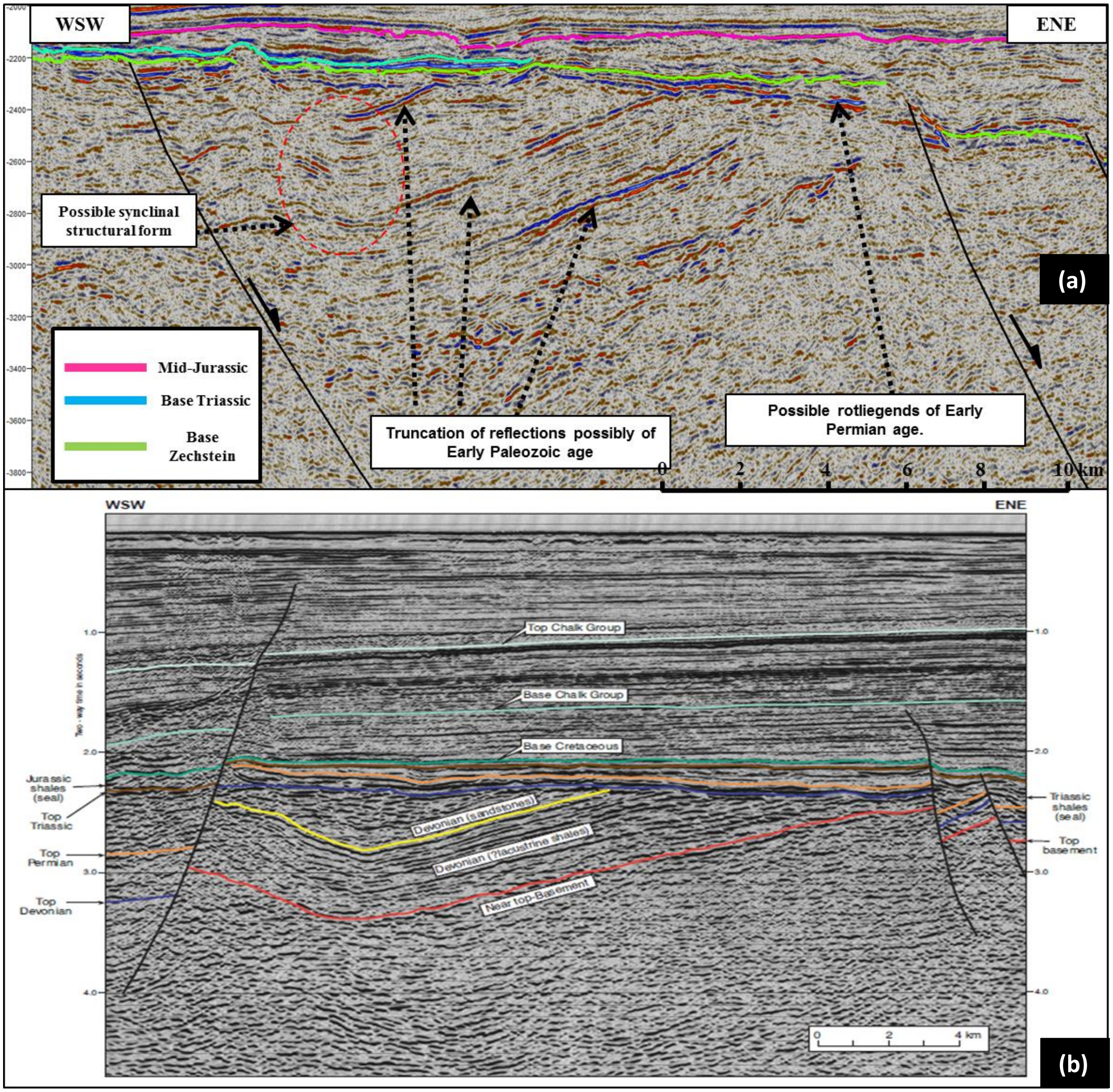


Figure 5.6: (a) Close-up of the Sele High from a Seismic Key Profile 4. A clear tilted large fault block can be observed on this basement high. Possible inversion caused by the Variscan compression during the Late Devonian-Early Carboniferous is encircled in red **(b)** Interpreted seismic section from the Sele High showing the same structure (Marshall and Hewett, 2003).

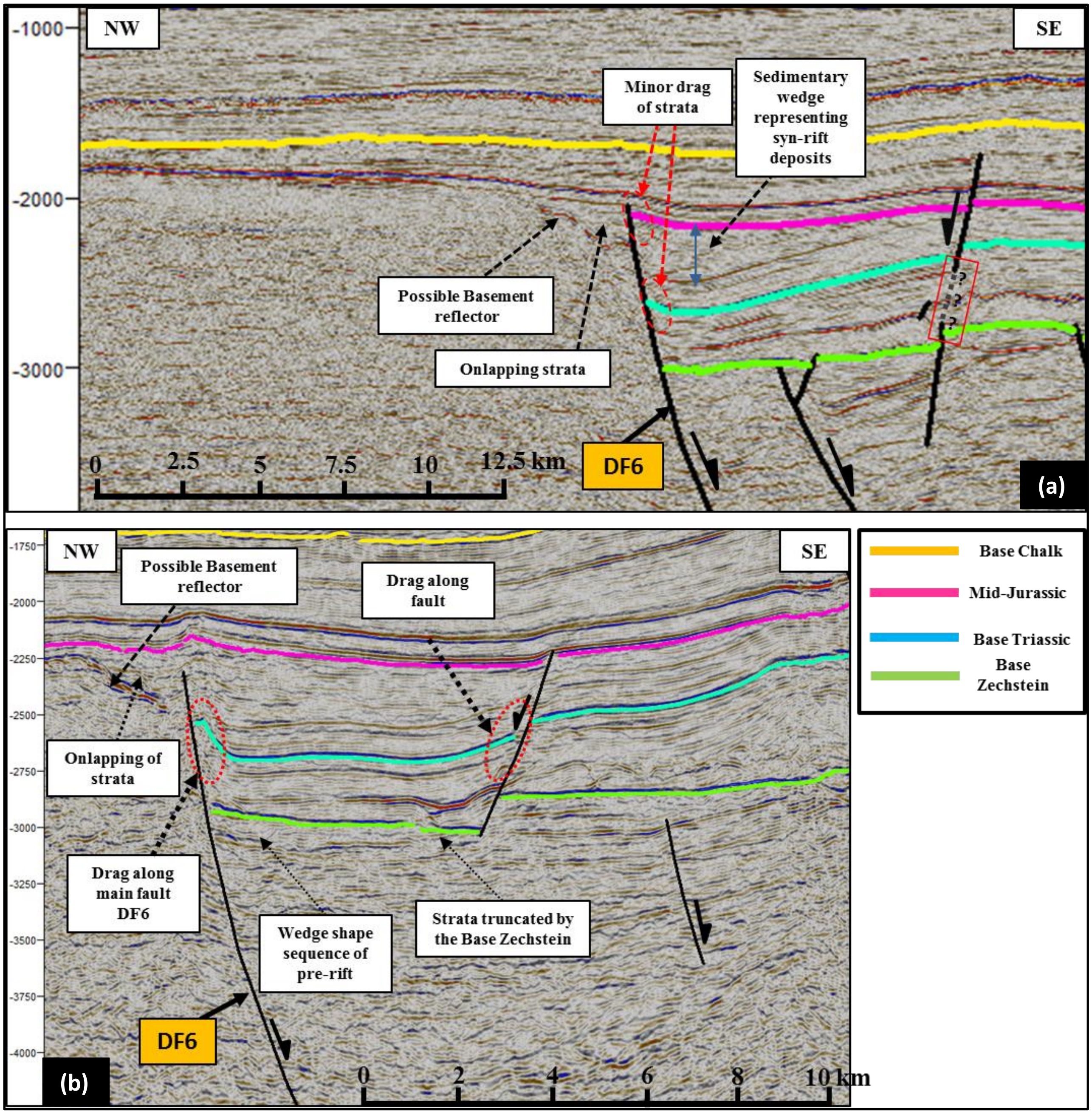


Figure 5.7: Upward propagation of DF6 and its antithetic fault. It is also representing the geological evolution of the Utsira High with respect to DF6. Close-ups **(a)** and **(b)** are taken from key profiles 1 and 2 respectively.

5.7. Half-graben geometries present below the Base Zechstein

The interpretation of faults and strata was carried out below the Base Zechstein group. Two wells in the Ling Depression, 17/4-1 & 17/12-2, included in this study (see table 3.1) have encountered the Rotliegend clastics and one recent well was drilled this year by Statoil (16/8-3 S) into the Rotliegend group in the Ling Depression (for details see chap. 1) (npd.no). So the well data have so far proven the presence of the Rotliegend clastics within the Ling Depression area.

Two general rifting stages are shown in figure 5.8 with the rotation of fault blocks. During syn-rift faults are active and rotating away from the basin axis. The continued sedimentation during syn-rift causes thickening of the sediments in the hanging wall towards the fault, away from basin axis.

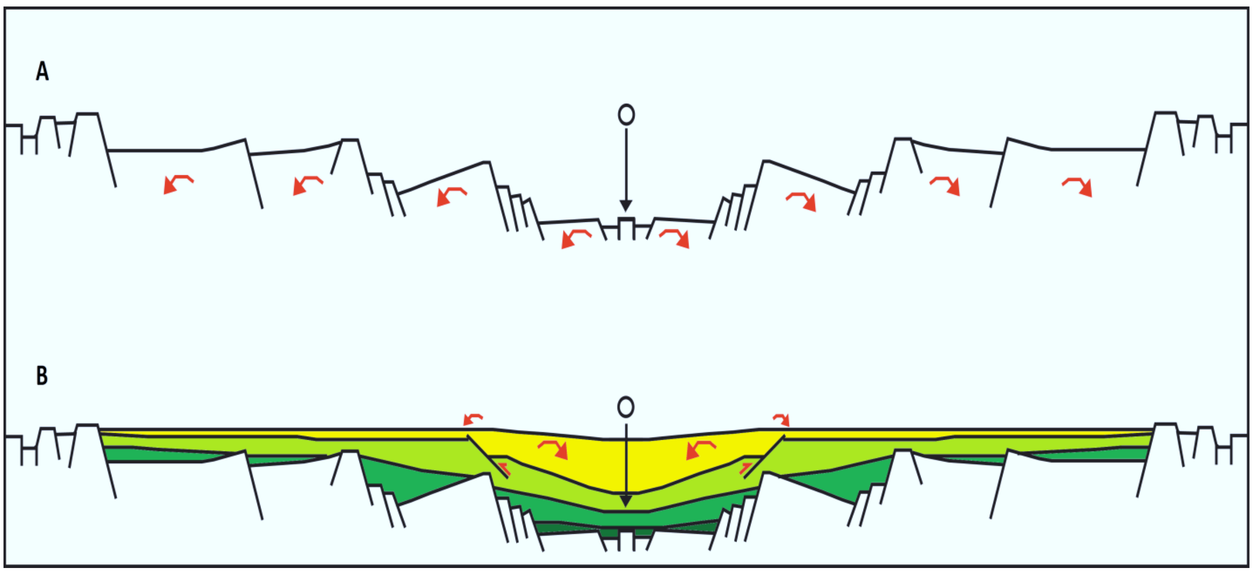


Figure 5.8: Two rift stages (A) syn-rift and (B) post-rift. Red arrows are showing the rotation of fault blocks (Gabrielsen et al., 1995; cited and modified from Gabrielsen, 2010).

Rotated fault blocks are observed in the Ling Depression below the Base Zechstein pointing towards the major rift event (fig. 5.9). This major rifting event occurred in the Late Carboniferous-Early Permian times. This event is proven in the Northern Permian Basin by the radiometric dating of volcanics and correlating the interpreted half-grabens with the well data from the surrounding areas of the Ling Depression (Heeremans and Faleide, 2004). In the Ling Depression, strata present in the hanging walls of the rotated half-grabens are truncated by the

Base Zechstein reflector and are thickening away towards the fault. These half-grabens observed in the Ling Depression are most likely related solely to the Late Carboniferous-Early Permian rifting event (fig. 5.9). Heeremans and Faleide (2004) also proposed the presence of the Rotliegend half-grabens below the Base Zechstein in the Ling Depression on the basis of their seismic data interpretations and data from the surrounding area.

5.8. Distribution of the Zechstein salt in the study area

The distribution of salt in the study area is defined by stratigraphic mapping of the salt and the structures affecting the northern edge of the Northern Permian Salt Basin. Thick salt sequences have been deposited in the Late Permian. The thermal relaxation and subsidence during the Early Permian developed the Northern and Southern Permian basins in the North Sea area which are filled with the upper Rotliegend clastics and the Zechstein carbonate\evaporate sequences (Heeremans and Faleide, 2004).

The possible lateral distribution of the Zechstein salt in the Northern Permian Basin, mapped during the study is shown in figure 4.2. Salt is present throughout the Ling Depression. But it is absent\eroded on some parts of the Sele High and is totally absent on the Utsira High with some probability of minor salt at the southern flanks (fig. 4.2). It is also present in the Southern Viking Graben upto the Beryl Embayment, but this part is not confined to the study.

Heeremans and Faleide (2004) suggested that the Ling Depression and the Åsta Graben are the structural elements which mark the northern boundary of salt in the Northern Permian Basin. They also proposed that the presence of a structural high between the Åsta Graben and the Stord Basin was the main structure that acted as a barrier for further propagation of salt towards north during the Late Permian. Well 17/3-1(Note: this well is not included in this study) was drilled on top of this structural high formed by two prominent half-grabens formed back-to-back. Basement was encountered in this well after the Smith Bank Formation of Early Triassic age because the Permian strata were completely absent/eroded (npd.no). The composite fault map (fig. 4.2) shows that MF1 and MF4 have opposite dip direction along there NE-SW lateral extent, probably showing the structural high which acted as a barrier during the Early-Late Permian. MF4 is a part of the Øygarden Fault Zone which is also related possibly to Late Carboniferous-Early Permian rifting (Færseth et al., 1995a). MF1 is showing the NE-SW strike on the Base

Zechstein fault map (fig. 4.18.a). Most probably it is rooting down to basement and again reactivated during the Late Carboniferous-Early Permian. Further towards the SW two faults with the NE-SW strike (DF6 and MF3) are marking the northern limit of the salt in the Northern Permian Basin (fig. 4.2). These two faults are bounding the Utsira High on the south. It is likely that the Utsira High was acting as a high-relief accommodation zone during the Early Permian which stopped further transgression of the Zechstein Sea during the Early-Late Permian times. It is also suggested in previous parts of discussion that DF6 was perhaps reactivated during the Late Carboniferous-Early Permian rifting which may have developed a high-relief accommodation zone.

The absence of the salt on the southeastern and the northeastern sides of the Sele High possibly point towards the presence of the paleo-highs during Early Permian time. These structural highs (Horst 3 and Horst 4) are mapped during the study (fig. 4.2). The salt was totally absent on these structures. Otherwise the Zechstein salt was interpreted on the remaining parts of the Sele High. The paleo-highs are also formed along the NE-SW trending deep faults which are probably running down into the basement and have affected the structure of the Sele High with the passage of time. The possible predicted ages of these horst structures coincides with the Late Carboniferous-Early Permian rifting event.

The above discussion possibly reveals that the distribution of the Zechstein salt was affected mostly by the NE-SW trending faults which are presumably genetically linked with the NE-SW trending ductile shear zone (Hardangerfjord Shear Zone) formed in the Early Devonian. Afterwards in the Late Carboniferous-Early Permian times these deep brittle faults reactivated due to regional rifting event, therefore producing horst geometries which hindered the salt distribution in the study area.

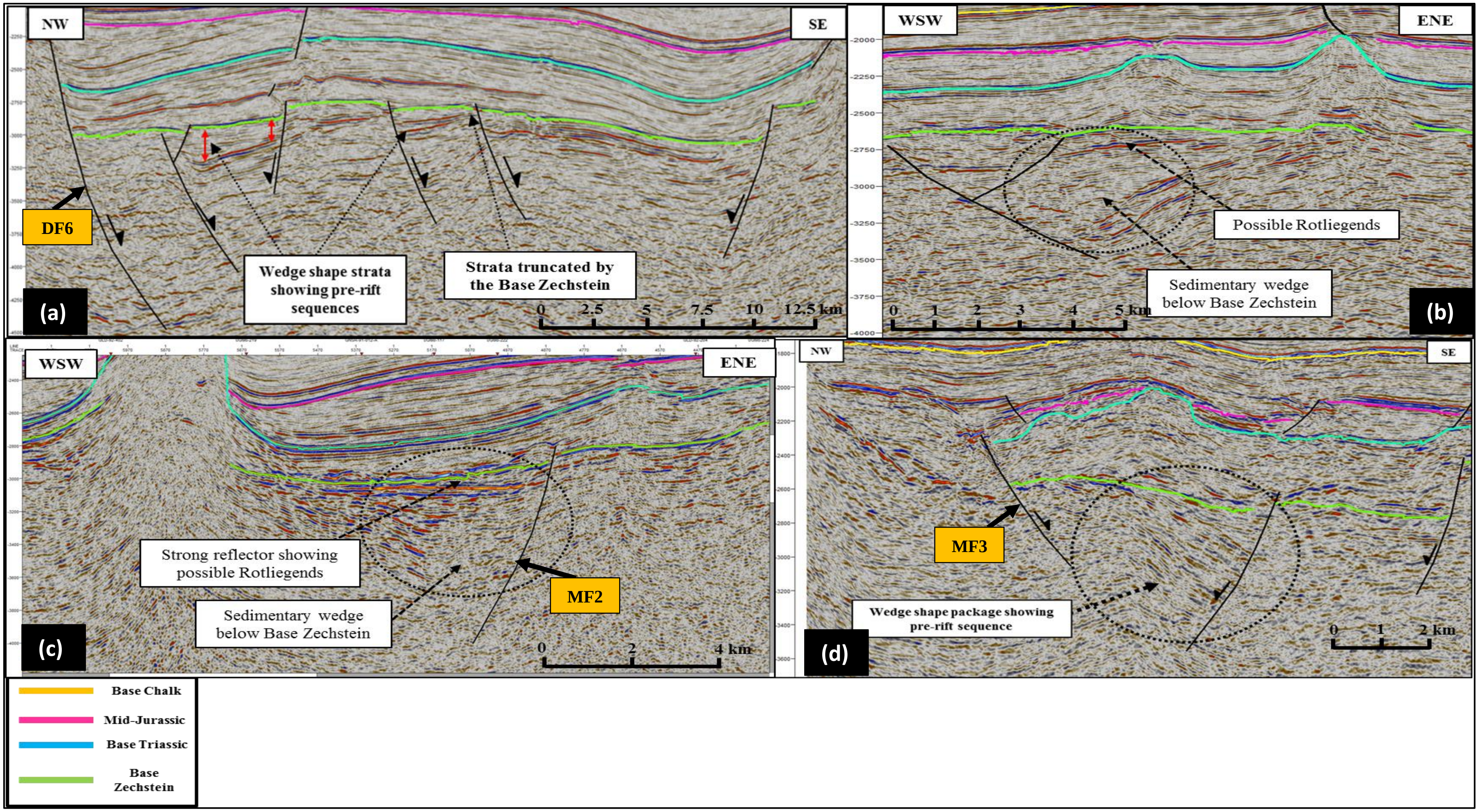


Figure 5.9: Rotated half-graben structures showing **s**yn-rift sedimentary wedges present below the Base Zechstein. (**a**), (**b**), (**c**) & (**d**) are showing close-ups of the Ling Depression from the key seismic profiles 1, 3, 4 & 5 respectively.

5.9. Lateral fault configuration

The Sele High is an interesting feature in terms of lateral structural settings as it is bounded by three major faults (MF2, MF5 & MF6) having different orientations (see fig. 4.2).

MF2 is oriented NE-SW and represents a structural separation between the Sele High and the Ling Depression (fig. 4.2). This fault is confined to the post-Zechstein structures. On the key profile 1, a fault is present below MF2 which is running deep into pre-Zechstein strata (fig. 4.3.a). The MF2 might be a possible continuation of this deep fault but it is not possible to structurally relate these two features due to the presence of salt layer in between. There can be a possibility that the deep fault is the result of the Late Carboniferous- Early Permian rifting and MF2 may have formed during the later rifting Phase occurring in the Mesozoic. The salt layer in this case maybe acting as a décollement, hence separating the per-Zechstein structures from the post-Zechstein structures. The MF2 strike direction also correlates with the NW-SE extensional event of the Late Jurassic. This leads to possible development of this main fault during the Late Jurassic rifting event.

MF5 is oriented NW-SE and is structurally separating the Sele High from the Norwegian-Danish Basin (fig. 4.2). This fault is also related to the post-Zechstein structures. The basement was characterized by NE-SW, NW-SE and E-W grains which resulted from Caledonian compression and further by Devonian extension (Færseth et al., 1995a). There is a possibility that this structural feature is related solely to the Late Jurassic extensional event but the orientation of this main fault does not satisfy the NW-SE to WNW-ESE extensional vectors. This leads to an argument that the reactivation of basement shear zones, which were formed in the NW-SE Devonian extensional settings, have possibly introduced complex geometries during the Late Jurassic rift event.

MF6 is the eastern boundary fault of the Sele High (fig. 4.2). It has the N-S strike direction which correlates with the E-W extensional vectors of the Late Carboniferous- Early Permian rifting. This fault is running deep into the crust. An argument can be build-up that this fault was formed initially by brittle continuation of the Hardangerfjord Shear Zone in the Late Devonian and later got reactivated during the Late Carboniferous-Early Permian rifting phase. The bounding faults of the Sele High have lateral variations along their trend which correlates with different tectonic events and extensional settings. Further detail studies on the orientation of these complex geometries can help understand the in-depth relationship between ductile shear zones and the major rifting events occurring lately in the North Sea

MF3 and DF6 mark the northern boundary of the Ling Depression and are oriented NE-SW. They represent the structural separation between the Utsira High and the Ling Depression (fig. 4.2). The dip direction of MF1 varies from the SE to SW during different periods with the change in the strike. It has opposite dip direction with respect to MF4 therefore forming a structural high (fig. 4.2). Heeremans and Faleide (2004) proposed that the basement high is present in between the Åsta Graben and the Stord Basin which probably acted as high relief zone most likely in the Early Permian. The Utsira High is also a basement high and the two main faults (MF3 and DF6), which are marking the southern limit of the Utsira High are showing a large offset between the Base Zechstein and the basement (see table 3.1). The faults with the NE-SW trends most probably root down into the basement subsequently reactivated during different extensional events occurring in later stages (Færseth, 1996). So the role of the NE-SW trending mega-structures (such as Hardangerfjord Shear Zone) in the crustal structuring and formation of complex geometries cannot be ruled out as suggested by some previous authors (e.g. Færseth, 1996; Smethurst,2000; Heeremans and Faleide, 2004).

CHAPTER 6

SUMMARY AND CONCLUSION

The Ling Depression has evolved through time along with the Utsira High and the Sele High. The main feature which played an important role in the geological evolution of the area includes the Hardangerfjord Shear Zone. Later some new features developed due to two major rifting events in the Late Carboniferous-Early Permian and Late Jurassic times. The old brittle faults also got reactivated during these rifting events, hence introducing complexities in the structures in the study area. The Zechstein salt played a major role as a décollement, thus separating the pre-Zechstein structures from the post-Zechstein structures. The summary of the timing of these main events is as follows:

- The rifting in the Early Devonian caused the formation of the NE-SW oriented ductile basement shear zones (such as Hardangerfjord Shear Zone).
- Continued rifting in the Late Devonian developed brittle faulting in the crust which is most likely a continuation of the ductile Hardangerfjord Shear Zone.
- In Early Carboniferous the regional Variscan compression presumably caused the inversion of Devonian extensional structures.
- Another major regional rifting event occurred in the Late Carboniferous-Early Permian times resulting in N-S oriented faults. This continued rifting developed rotated half-grabens and also reactivated some deep-rooted faults most likely related to the Devonian extensional event. Perhaps the Utsira High and some parts of the Sele High were uplifted during the Early Permian, therefore acting as high relief accommodation zones. While subsidence due to thermal relaxation formed two large Permian basins (Northern and Southern Permian basins).
- During the Late Permian, the Zechstein salt was deposited in the Permian salt basins. Basement highs acted as barrier towards the North, therefore hindering the deposition of salt further to the north into the Stord Basin.
- During the Early Triassic an increase in sedimentation rate remained generally balanced with the rate of subsidence which resulted in thick accumulation of Triassic deposits.

- Salt movement was triggered most likely in the Middle Triassic due the thick Triassic deposits overlying the Zechstein salt. The movement in the salt developed local folding and diapirism.
- Early Jurassic experienced another event of volcanism. This further developed the rift dome structure in the central North Sea.
- In mid-Late Jurassic another major rifting event is characterized by NNE-SSW structural orientation. Some deep-rooted faults were probably reactivated again which caused the further uplift of the Utsira High and the Sele High.
- The Alpine compression mostly caused inversion of structures at the shallower depth. Along with some local salt induced inversion, as the halokinesis continued in the Cenozoic.

REFERENCES

ABRAMOVITZ, T., THYBO, H. & MONA LISA WORKING GROUP 1998. Seismic structure across the Caledonian deformation front along MONA LISA profile 1 in the southeastern North Sea. . *Tectonophysics*, 288 (1–4)**,,** 153–176.

ABRAMOVITZ, T., LANDES, M., THYBO, H., JACOB, A. W. B. & PRODEHL, C. 1999. Crustal velocity structure across the Tornquist and Iapetus Suture Zones—a comparison based on MONA LISA and VARNET data. . *Tectonophysics* 314 (1–3), **,** 69– 82.

ABRAMOVITZ, T. & THYBO, H. 2000. Seismic images of Caledonian, lithosphere-scale collision structures in the southeastern North Sea along Mona Lisa Profile 2. *Tectonophysics,* 317**,** 27-54.

AFTAB, J. M. 2012. Late Carboniferous-Early Permian structural development of the Ringkøbing Fyn High and adjacent Norwegian-Danish Basin. *MSc dissertation-Geosciences, Faculty of Mathematics and Natural Sciences, Uni. of Oslo*.

ANDERSEN, T. B. & JAMTVEIT, B. 1990. Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord Region of western Norway. *Tectonics,* 9**,** 1097-1111.

ANDERSEN, T. B. 1998. Extensional tectonics in the Caledonides of southern Norway, an overview. *Tectonophysics, 285***,** 333-351.

ANDERSEN, T. B., TORSVIK, T. H., EIDE, E. A., OSMUNDSEN, P. T. & FALEIDE, J. I. 1999. Permian and Mesozoic extensional faulting within the Caledonides of the central south Norway. *Journal of the Geological Society, London,* 156**,** 1073-1080.

ARMSTRONG, M. & PATERSON, I. B. 1970. . The Lower Old Red Sandstone of the Strathmore Region. *Report of the Institute of Geological Sciences, No. 70/12.*

BARTHOLOMEW, I. D., PETERS, J. M. & POWELL, C. M. 1993. Regional structural evolution of the North Sea: oblique slip and the reactivation of basement lineaments. *Petroleum Geology Conference series,* 4**,** 1109-112.

BASSETT, M. G. 2003. Sub-Devonian geology. 61-63 in The Millennium Atlas: Petroleum geology of the central and northern North Sea. Evans, D., Graham, C., Armour, A. & Bathurst, P. (editors and coordinators). (London: The Geological Society of London).

BERTHELSEN, A. 1993. Where different geological philosophies meet: the Trans-European Suture Zone, *in: Gec. D.D., Beckholmen. M. (Eds) EUROPROBE symposium. Jablona 1991 Publ. Inst. Geophys. Pol. Acad. Sci. A-20: 225, Warsaw,* **,** 19-31

BIRKELUND, T. & PERCH-NIELSEN, K. 1976. Late Palaeozoic-Mesozoic evolution of central East Greenland. *Geology of Greenland***,** 304-339.

BLUCK, B. J. 2001. Caledonian and related events in Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* Vol. 91 **,** 375-404.

BØE, R., FOSSEN, H. AND SMELROR, M. (2010) Mesozoic sediments and structures onshore Norway and in the coastal zone. Norges geologiske undersøkelse Bulletin, 450,15-32.

BRUCE, D. R. S. & STEMMERIK, L. 2003. Carboniferous. 83-89 in The Millennium Atlas: Petroleum geology of the central and northern North Sea. Evans, D., Graham, C., Armour, A. & Bathurst, P. (editors and coordinators). (London: The Geological Society of London).

BURG, J. P., VAN DEN DRIESSCHE, J. & BRUN, J. P. 1994. Syn- to post-thickening extension in the Variscan Belt of Western Europe: modes and structural consequences. *Geologie de la France,* 3**,** 33-51.

CAMERON, I. B. & STEPHENSON, D. 1985. British Regional Geology: the Midland Valley of Scotland (third edition). *London: HMSO for the British Geological Survey*.

DEEGAN, C. E, & SCULL, B. J. 1977. A standard lithostratigraphic nomenclature for the Central and Northern North Sea. Report of the Institute of Geological Sciences, No. 77/25. *Bulletin of the Norwegian Petroleum Directorate,* No. 1. 4-6.

ENFIELD, M. A. & COWARD, M. P. 1987. The structure of the West Orkney Basin, northern Scotland. *Journal of the Geological Society of London,* Vol. 144**,** 871-884.

FÆRSETH, R. B., GABRIELSEN, R. H. & HURICH, C. A. 1995a. Influence of basement in structuring of the North Sea basin, offshore southwest Norway. *Norsk Geologisk Tidsskrift, 75***,** 105-119.

FÆRSETH, R. B. 1996. Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea. *Journal of the Geological Society of London,* 153**,** 931-944.

FOSSEN, H. 1992. The role of extensional tectonics in the Caledonides of south Norway. *Journal of structural geology,* 14**,** 1033-1046.

FOSSEN, H. & RYKKELID, E. 1992a. Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance. *Geology,* 20**,** 737-740.

FOSSEN, H. & HURICH, C. A. 2005. The Hardangerfjord Shear Zone in SW Norway and the North Sea: a large-scale low-angle shear zone in the Caledonian crust. *Journal of the Geological Society,* 162**,** 675-687.

FOSSEN, H. 2010. Extensional tectonics in the North Atlantic Caledonides: a regional view. *Geological Society, London, Special Publications,* 335**,** 767-793.

FREDERIKSEN, S., NIELSEN, S.B. & BALLING, N. 2001. A numerical dynamic model for the Norwegian-Danish Basin. Tectonophysics, 343, 165-183.

FROST, T. T. C., FITCH, F. J. & MILLER, J. A. 1981. The Age and Nature of the Crystalline Basement of the North Sea Basin. *In: Illing, L.V., Hobson, G.C. (Eds.), Petroleum Geology of the Continental Shelf of North West Europe. Heyden, London***,** 43– 57.

GABRIELSEN, R.H., STEEL, R.J. & NØTTVEDT, A. 1995. Subtle traps in extensional terranes: A model with reference to the North Sea. Petroleum Geoscience 1, 223–235.

GABRIELSEN, R. H. 2010, The structure and hydrocarbon traps of sedimentary basins, In: Bjørlykke, K. (ed.), Petroleum geoscience from sedimentary environments to rock physics, Springer, Berlin, 299-327.

GIBB, F.G.F. & KANARIS-SOTIRIOUS, R. 1976 Jurassic igneous rocks of the Forties Field - Nature 260: 23-25.

GLENNIE, K. 1972. Permian Rotliegendes of northwest Europe interpreted in light of modern desert sedimentation studies. *AAPG Bulletin,* 56**,** 1048-1071.

GLENNIE, K.W. 1998. Lower Permian, Rotliegend. In: Glennie, K.W. (ed) Petroleum geology of the North Sea; basic concepts and recent advances. *Blackwell Science Geology & Petroleum Geology, Oxford, United Kingdom*, 137-173.

GLENNIE, K.W., HIGHAM, J. & STEMMERIK, L. 2003. Permian. In: Evans, D., Graham, C., Armour, A. & Bathurst, P. (eds) *The Millenium Atlas. Geological Society, London,* 91-103.

GOLDSCHMIDT, V. M. 1912. Die kaledonische Deformation der su¨d-norwegischen Urgebirgstafel. Skr. Vidensk. Selsk., Christiania19,. 11.

GRADSTEIN, F. M., OGG, J. G., SCHMITZ, M. & OGG, G. 2012, The Geologic Time Scale 2012. *Published by Elsevier*.

GRAVERSEN, O. The Jurassic-Cretaceous North Sea Rift Dome and Associated Basin Evolution. AAPG Annual Convention, Calgary, Alberta, 2005.

HAUGHTON, P. D. W. & BLUCK, B. J. 1988. Diverse alluvial sequences from the Lower Old Red Sandstone of the Strathmore region, Scotland and implications for the relationship between late Caledonian tectonics and sedimentation. *in Devonian of the World. MCMILLAN, N J, EMBRY, A F, and GLASS, D J (editors). Memoir of the Canadian Society of Petroleum Geologists,* No. 14**,** 269-293.

HEEREMANS, M. & FALEIDE, J. I. 2004. Late Carboniferous-Permian tectonics and magmatic activity in the Skagerrak, Kattegat and the North Sea. *SPECIAL PUBLICATION-GEOLOGICAL SOCIETY OF LONDON,* 223**,** 157-176.

HEEREMANS, M., FALEIDE, J. I. & LARSEN, B. T. 2004b. Late Carboniferous - Permian of NW Europe: an introduction to a new regional map. In: Wilson, M., Neumann, E.R., Davies, G. R., Timmerman, M. J., Heeremans, M., & Larsen, B. T. (eds) Permo-Carboniferous Rifting in NW Europe, *Geological Society, London, Special Publication,* 223, 78-85.

HEYBROEK, P. 1974. Explanation to tectonic maps of the Netherlands. *Geol. Mijnbouw,* 53**,** 43-50.

HEYBROEK, P. 1975. The structure of the Dutch part of the Central North Sea graben. *In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe,* vol. 1. Geology - Applied Sci. Publ**,** 339-352.

HOWITT, F., E.R. ASTON & M. JAQUE 1975. The occurrence of Jurassic volcanics in the North Sea. In: A.W. Woodland (ed.): *Petroleum and the continental shelf of NW Europe, vol. 1 Geology Applied Sci. Pub*. 379-386.

LYNGSIE, S. B., THYBO, H. & RASMUSSEN, T. 2006. Regional geological and tectonic structures of the North Sea area from potential field modelling. *Tectonophysics,* 413**,** 147-170.

MAROTTA, A. M. & SABADINI, R. 2003. Numerical models of tectonic deformation at the Baltica–Avalonia transition zone during the Paleocene phase of inversion. *Tectonophysics,* 373**,** 25-37.

MARSHALL, J. E. A. 1991. Palynology of the Stonehaven Group, Scotland: evidence for a Mid Silurian age and its geological implications. *Geological Magazine,* Vol. 128**,** 283-286.

MARSHALL, J. E. A. & HEWETT, A. J. 2003. Devonian. The Millennium Atlas: petroleum geology of the central and northern North Sea. Evans, D, Graham, C, Armour, A, and Bathurst, P (editors and co-ordinators). *The Geological Society of London***,** 65-81.

MCCLAY, M., CONEY, P. & DAVIS, G. 1986. Collapse of the Caledonian orogen and the Old Red Sandstone.

MILNES, A. G., WENNBERG, O. P., SKÅR, Ø. & KOESTLER, A. G. 1997. Contraction, extension and timing in the South Norwegian Caledonides: the Sognefjord transect. *In: Burg, J.-P. & Ford, M. (eds) Orogeny through Time. Geological Society, London, Special Publications,* 121**,** 123-148.

MONA LISAWORKING GROUP 1997b. . Deep seismic investigations of the lithosphere in the southeastern North Sea. . *Tectonophysics* 269, **,** 1– 19.

MURPHY, J. B. & NANCE, R. D. 2008. The Pangea conundrum. *Geology* 36;**,** 703-706.

NEUMANN, E.R., WILSON, M., HEEREMANS, M., DUNWORTH, L.A., OBST, K., TIMMERMAN, M.J. & KIRSTEIN, L.A. 2003. Carboniferous-Permian rifting and magmatism in northern Europe: A review. In: Wilson, M., Neumann, E.R., Davies, G., Timmerman, M.J., Heeremans, M. & Larsen, B.T. (eds) Permo-Carboniferous Rifting in NW Europe. *Geological Society, London, Special Publication, this volume*, yy-zz.

NORTON, M. G., MCCLAY, K. R. & WAY, N. A. 1987. Tectonic evolution of Devonian basins in northern Scotland and southern Norway. *Norsk Geologisk Tidsskrift, 75,* Vol. 67**,** 323-338.

OLESEN, O., LUNDIN, E. & NORDGULEN, Ø. E. A. 2002. Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. *Norwegian Journal of Geology,* , 82**,** 243-262.

RAWSON, P. F. & RILEY, L. A. 1982. Latest Jurassic-early Cretaceous events and the 'Late Cimmerian unconformity' in the North Sea area. *Am. Assoc. Petrol. Geol. Geol.,Bulletin***,** 2628-48.

REY, P., BURG, J. P. & CASEY, M. 1997. The Scandinavian Caledonides and their relationship to the Variscan belt. *In: BURG, J.P. & FORD, M. (eds) Orogeny Through Time. Geological Society, London, Special Publications,* 121**,** 179-200.

ROSENDAHL, B. R. 1987. Architecture of continental rifts with special reference to East Africa. *Ann. Rev. Earth Planet. Sci,* 15**,** 445-503.

SCHÆRER, U. 1980. . Geologie und U–Pb/Sr–Sr Geochronologie der kaledonischen Jotundecke im Tyingebiet, Sudnorwegen. Dissertation, ETH Zurich.

SEGURET, M., SERANNE, M., CHAUVET, A. & BRUNEL, M. 1989. Collapse basin: A new type of extensional sedimentary basin from the Devonian of Norway. *Geology,* Vol. 17, 127-130.

SÉRANNE, M. & SEGURET, M. 1987. The Devonian basins of western Norway: tectonics and kinematics of an extending crust. *Geological Society, London, Special Publications,* 28**,** 537-548.

SÉRRANE, M. 1992. Devonian extensional tectonics versus Carboniferous inversion in the northern Orcadian basin. *Journal of the Geological Society of London,* Vol. 149**,** 27-37.

SKILBREI, J. R., OLESEN, O., OSMUNDSEN, P. T., KIHLE, O., AARO, S. & FJELLANGER, E. 2002. A study of basement structures and onshore–offshore correlations in Central Norway. *Norwegian Journal of Geology,* , 82**,** 263-279.

SMETHURST, M. 2000. Land–offshore tectonic links in western Norway and the northern North Sea. *Journal of the Geological Society,* 157**,** 769-781.

SOPER, N., WEBB, B. & WOODCOCK, N. 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society,* 46**,** 175-192.

STEWART, S. A. & COWARD, M. P. 1994, Synthesis of salt tectonics in the southern North Sea, UK. *Marine and Petroleum Geology,* , Vol. 12, No. 5, **,** pp. 457-475.

STOREDVEDT, K. M. 1973 A possible large-scale sinistral displacement along the Great Glen fault in Scotland. *Geol. Mag.* , 111**,** 23-30.

THYBO, H., 1990. A seismic velocity model along the EGT profile—from the North German Basin into the Baltic Shield. In: Freeman, R., Giese, P., Mueller, S. (Eds.), The European Geotraverse, Integrative Studies, Rauischholzhausen, Germany, pp. 99– 108.

THYBO, H., 1997. Geophysical characteristics of the Tornquist fan area, northwest Trans-European Suture Zone: indication of late Carboniferous to early Permian dextral transtension. *Geological Magazine* 134 (5), 597–606.

THYBO, H., 2001. Crustal structure along the EGT profile across the Tornquist fan interpreted from seismic, gravity and magnetic data. *Tectonophysics* 334 (3–4), 155–190.

UNDERHILL, J. R. & BRODIE, J. A. 1993. Structural geology of Easter Ross, Scotland: implications for movement on the Great Glen fault zone. *Journal of the Geological Society of London,* Vol. 150**,** 515-527.

VAN WEES, J.D., STEPHENSON, R.A., ZIEGLER, P.A., BAYER, U., MCCANN, T., DADLEZ, R., GAUPP, R., NARKIEWICZ, M., BITZER, F. & SCHECK, M. 2000. On the origin of the Southern Permian Basin, Central Europe. *Marine and Petroleum Geology*, 17, 43-59.

WILLIAMS, G. D., POWELL, C. M. & COOPER, M. A. 1989. Geometry and kinematics of inversion tectonics. *Geological Society, London, Special Publications,* 44**,** 3-15.

WILLIAMSON, J. P., PHARAOH, T. C., BANKA, D., THYBO, H., LAIGLE, M. & LEE, M. K. 2002. Potential field modelling of the Baltica–Avalonia (Thor-Tomquist) suture beneath the southern North Sea. *Tectonophysics,* 360 (1–4)**,** 47– 60.

WILLSEY, S. P., UMHOEFER, P. J. & GEORGE, E. H. 2002. Early evolution of an extensional monocline by a propagating normal fault: 3D analysis from combined field study and numerical modelling. *Journal of structural geology,* 24**,** 651-669.

WOODCOCK, N. & STRACHAN, R. 2000. Geological history of the British Isles. Blackwell Science, Oxford, UK.

ZIEGLER, P. A. 1975. Geologic evolution of North Sea and its tectonic framework. *Bull. A.A.P.G. ,* 59**,** 1073-1097.

ZIEGLER, P. A. 1978. North-Western Europe: tectonics and basin development. *In: A. J. van Loon (ed.): Key-notes of the MEGS-II (Amsterdam, 1978). Geol. Mijnbouw,* 57**,** 589-626.

ZIEGLER, P.A. 1982. Geological atlas of Western and Central Europe. Elsevier, Amsterdam, Netherlands, 130.

ZIEGLER, P. A. 1988. Evolution of the Arctic-North Atlantic rift system. *Am. Assoc. Petrol. Geol. Mem.,* 43**,** 198.

ZIEGLER, P. A. 1990. *Geological Atlas of Western and Central Europe: 1990,* Geological Society.

ZIEGLER, W. H. 1975. Outline of the geological history of the North Sea, in Petroleum and the continental shelf of northwest Europe: Barking, U. K., Applied Schience Publishers Ltd., V. l , p . 165-190.

www.npd.no